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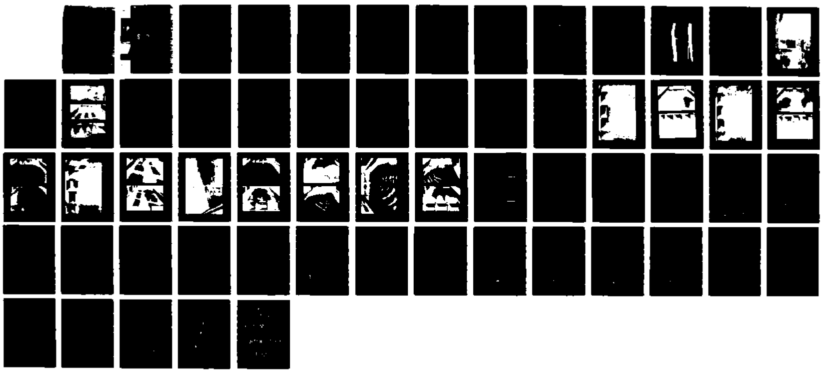

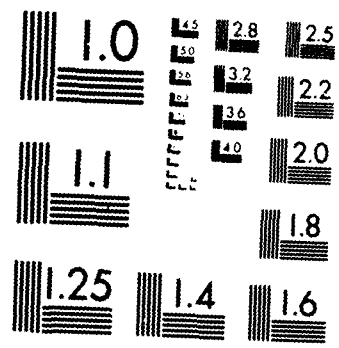

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US Army Corps of Engineers

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SCOUR PROTECTION FOR PIKE ISLAND DAM, OHIO RIVER

Hydraulic Model Investigation

by

John E. Hite, Jr.

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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Pike Island Locks and Dams are located 84.2 miles below the head of the Ohio River at Pittsburgh, Pennsylvania. The navigation project contains a gated spillway section with a stilling basin. Tests were conducted on a 1:25-scale section model of five of the nine spillway tainter gates and the stilling basin. The purpose of the model study was to determine sizing and configuration of materials necessary to protect the area immediately downstream from the stilling basin from additional scour. Scour protection was developed for operation with a single gate opened 10 ft, normal upper pool, and minimum project tailwater. This type operation occurs when ice and debris are passed through the spillway gates.

The type 2 riprap plan, which consisted of 4- to 6-ft-diameter stones, remained stable for the conditions described when placed on a 1V on 3H downward slope. The type 2 riprap plan was modified to accommodate construction by adding a horizontal section of tremie

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concrete followed by grout-filled fabric bags immediately downstream from the stilling basin. Riprap consisting of 5-ft-diameter stones was then placed on a 1V on 3H downward slope just downstream of the grout-filled fabric bag. This plan was stable for operation with a single gate opened 10 ft, normal upper pool, and minimum project tailwater and was recommended for the Pike Island Project.

PREFACE

The model investigation reported herein was authorized by the Office, Chief of Engineers (OCE), US Army, on 1 October 1983 at the request of the US Army Engineer District, Pittsburgh (ORP).

The studies were conducted by personnel of the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), during the period March 1984 to February 1985 under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL, and J. L. Grace, Jr., Chief of the Hydraulic Structures Division. The tests were conducted by Messrs. T. E. Murphy, Jr., and J. E. Hite, Jr., Locks and Conduits Branch, under the supervision of Mr. J. F. George, Chief of the Locks and Conduits Branch. This report was prepared by Mr. Hite.

The model was constructed by Mr. Bobby Blackwell, under the supervision of Mr. Sid Leist, Engineering and Construction Services Division.

Messrs. Bruce McCartney of OCE; Laszlo Varga of the US Army Engineer Division, Ohio River; and Ed Kovanic, Robert W. Schmitt, Joe Coletti, and Ray Povirk, ORP, visited WES during the course of the model study to observe model operation and correlate results with design studies.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

TABLE OF CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms

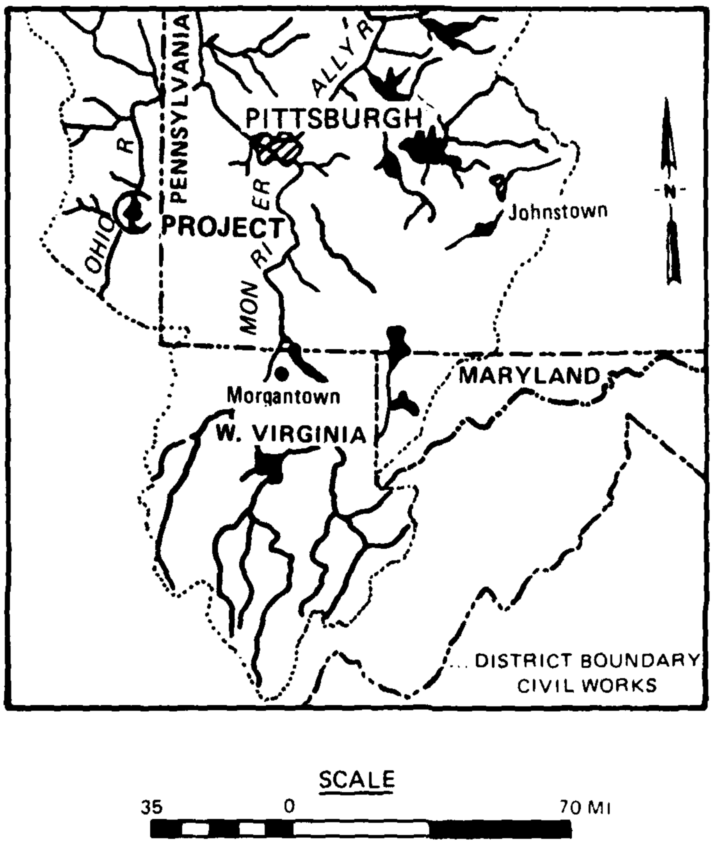

Figure 1. Vicinity map

SCOUR PROTECTION FOR PIKE ISLAND DAM, OHIO RIVER

Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. Pike Island Locks and Dam are located 84.2 miles* below the head of the Ohio River at Pittsburgh, Pennsylvania (Figure 1). The project consists of two lock chambers, 110 by 1200 ft and 110 by 600 ft, with appurtenant walls and approach channels, and a spillway with its center section surmounted by nine 110-ft-wide tainter gates and a 110-ft-long uncontrolled section on the right side (looking downstream) of the gated section (Figure 2). The crest of the gated section is at elevation 617.0 and the tops of the gates and the crest of the uncontrolled section are at el 646.0**. The center three gates and the gate at each end of the gated section were designed as submergible gates, but are no longer operated in this manner. The remaining four gates are nonsubmergible. A stilling basin at el 608.0 was constructed below the spillway gates and dimensions and elevations of pertinent features of the gated spillway and stilling basin are shown in Plate 1.

2. A model study of the Pike Island spillway and stilling basin was conducted at the US Army Engineer Waterways Experiment Station (WES) in 1959†. A section model was constructed to a linear scale ratio of 1:25 and the model tests were performed in a 1-ft-wide glass-sided flume. The purpose of that model investigation was to verify the adequacy of the stilling basin and to develop optimum size and arrangement of stilling basin elements for maximum energy dissipation. A stilling basin that performed satisfactorily for flows from either the submergible or nonsubmergible gates was developed.

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* A table of factors for converting non-SI units of measurement to metric (SI) units is presented on page 3.

** All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

† E. S. Melsheimer and T. E. Murphy. 1961 (Dec). "Spillway and Stilling Basin for Pike Island Locks and Dam, Ohio River," Technical Report No. 2-586, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

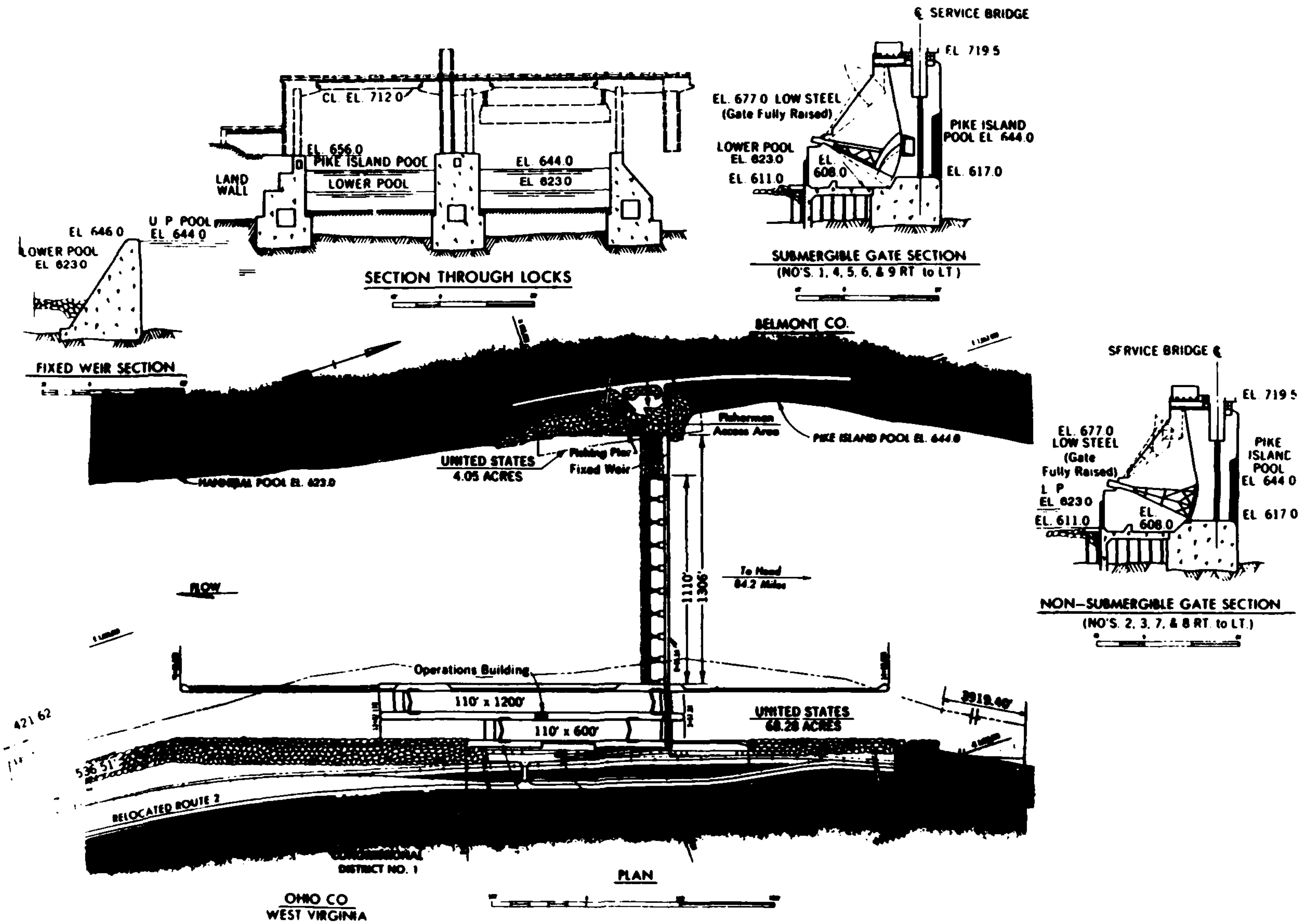


Figure 2. Plan and sections

3. Soundings recorded downstream from the structure over the past several years indicated considerable scour in the outflow channel and immediately downstream of the end sill. Much of the piling supporting the stilling basin has been exposed and many of the downstream bulkhead pads (see Figure 3) have scour around them. The original riprap protection was placed horizontally for 50 ft downstream from the end of the stilling basin as shown in Plate 1. The contract for the stone protection and placement stated "approximately 75 percent of the entire quantity of stone shall weigh between 4,000 lbs and 12,000 lbs and the remainder shall be stones grading down from 4,000 lbs to 150 lbs and should be suitable for filling voids between the larger stones. The stone shall be in pieces generally rectangular in cross section, the least dimension of any one piece being not less than one-third its greatest dimension." A portion of the stone protection placed downstream of the stilling basin during construction of the project is shown in Figure 3.

4. Since the project has been in operation, scour below the stilling basin has occurred across the entire width of the channel below the basin. The original stone protection has been displaced by undercutting; loss of material beneath the rock (piping); by adverse flow conditions caused during ice and debris passage; or a combination of all of these. Soundings recorded in June 1983 indicated that there were areas in the downstream channel that had scoured to a depth approximately 30 ft lower than when the project was first constructed exposing the piling underneath the stilling basin apron. If the scour below the stilling basin continues, structural damage will occur.

Purpose of Model Study

5. The purpose of the model study was to develop a scour protection plan that would repair the area immediately downstream from the stilling basin and prevent future scouring of this area. Also, the model was used to determine operational guidance for avoiding flow conditions that cause scour downstream from the structure.

Figure 3. Pike Island Dam under construction

PART II: THE MODEL

Description

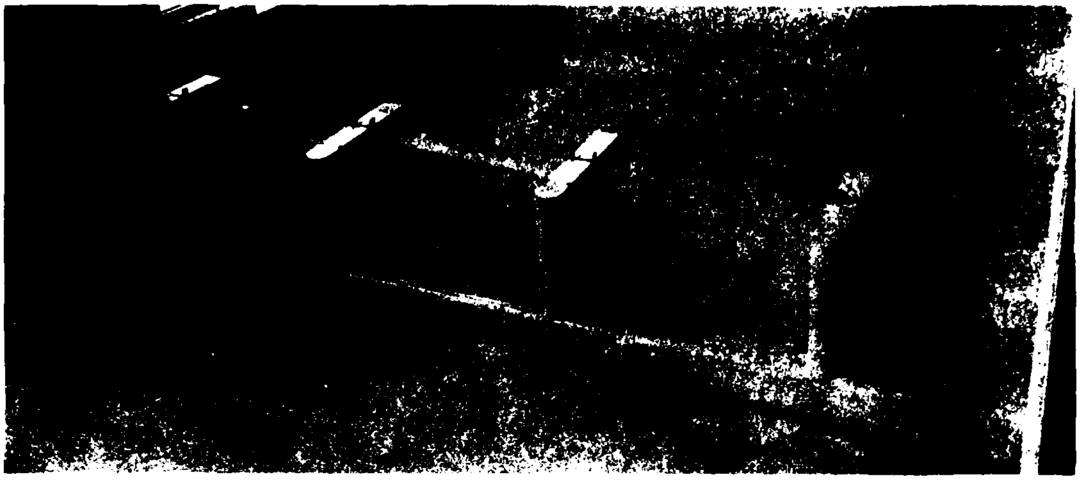
6. The model (Figure 4) was constructed to an undistorted scale of 1:25 and reproduced five of the nine gate bays, approximately a 500-ft-length of topography upstream from the structure, the spillway and spillway gates, the stilling basin, the proposed scour protection plan, and approximately a 1,000-ft-length of the exit channel. The spillway and spillway gates were fabricated of sheet metal and the stilling basin apron was constructed of plastic-coated plywood. The baffle blocks, end sill, and bulkhead pads were constructed of wood and treated with a waterproofing compound to prevent swelling. The upstream topography was molded of sand and cement mortar to sheet metal templates and the exit channel was molded of sand and the proposed riprap.

Model Appurtenances

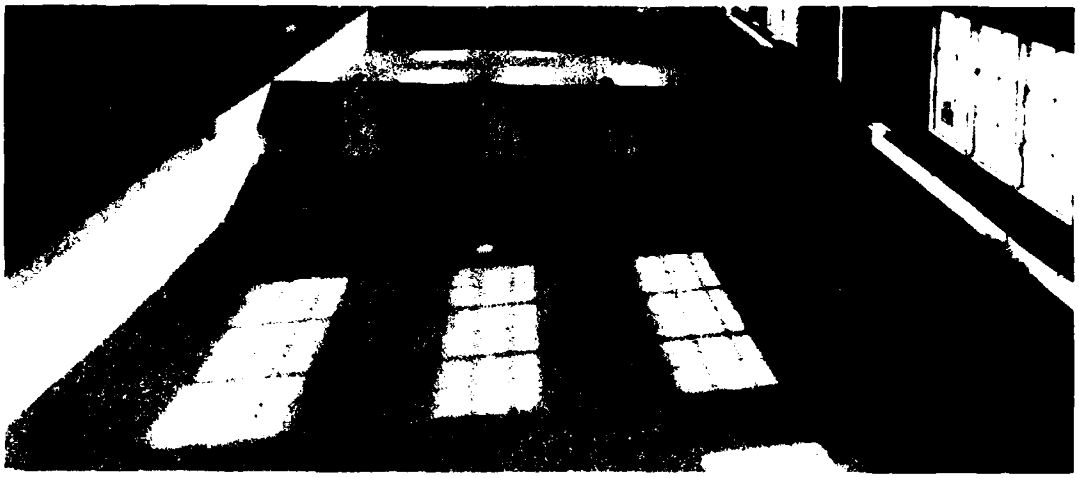
7. Water used in operation of the models was supplied by a circulating system. Discharges in the model, measured with venturi meters installed in the inflow lines, were baffled when entering the model. Water-surface elevations and soundings over the sand and riprap beds were measured with point gages. Velocities were measured with pitot tubes mounted to permit measurement of flow from any direction and at any depth. The tailwater in the lower end of the model was maintained at the desired depth by means of an adjustable tailgate. Different designs, along with various flow conditions, were recorded photographically.

Scale Relations

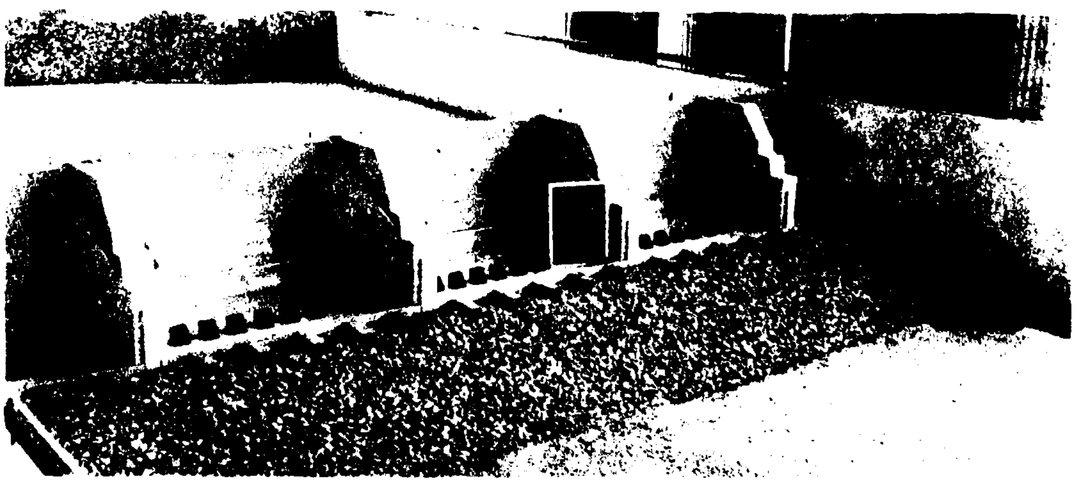
8. The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transference of model data to prototype equivalents are



a. Looking downstream



b. Looking upstream



c. Looking upstream

Figure 4. General views of model

presented below:

Characteristic	Dimension*	Model:Prototype
Length	L_r	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Volume	$Q_r = L_r^{5/2}$	1:3,125
Weight	$W_r = L_r^3$	1:15,625
Time	$T_r = L_r^{1/2}$	1:5

*Dimensions are in terms of length.

Because of the nature of the phenomena involved, certain model data can be accepted quantitatively, while other data are reliable only in a qualitative sense. Measurements in the model of discharges, water-surface elevations, velocities, and resistance to displacement of riprap material can be transferred quantitatively from model to prototype by means of the above scale relations. Evidence of scour of the model sand bed, however, is to be considered only as qualitatively reliable since it has not yet been found possible to reproduce quantitatively in a model the relatively greater extent of erosion that occurs in the prototype with fine-grained bed material. Data on scour tendencies provided a basis for determination of the relative effectiveness of the different designs and indicated the areas most subject to attack.

PART III: TESTS AND RESULTS

9. A spray curve was developed for the stilling basin with single gate operations and is shown in Plate 2. To develop the curve, the tailwater was gradually lowered for each of six different gate opening until the depth became insufficient to maintain a hydraulic jump and the flow began to spray off the baffle blocks. This is an adverse flow condition and should be avoided due to the extreme turbulence that occurs. This type flow condition scours the area downstream from the structure. A spray condition is shown in Photo 1 for an 8-ft gate opening. The flow sprayed off the baffle blocks with minimum tailwater (el 623) for all gate openings greater than 5 ft.

10. Tests were conducted to determine the minimum gate opening that would pass ice adequately. Ice problems at navigation projects generally occur during periods of low flow and subsequently low tailwater. Ice passage usually requires a relatively large gate opening and this type operation is believed to be a main cause of the scour downstream from the navigation structures. Ice blocks ranging in size from 2 ft by 2 ft by 1.5 ft thick to 10 ft by 10 ft by 1.5 ft thick were simulated using a polyethylene material with the same density as ice. The blocks were placed in the model upstream from the dam and allowed to pass through the stilling basin and float downstream. An 8-ft-gate opening was determined to be the minimum opening where ice passed under the gate adequately with a normal tailwater elevation (635.4 for this gate setting). During these tests, the upper pool was el 644, normal for the Pike Island Project, and the tailwater elevations were set according to a gate operation schedule furnished by the Pittsburgh District (ORP).

11. Tests were conducted to determine the stability of various protective plans downstream from the structure. The type 1 riprap plan, which consisted of the gradation shown in Plate 3, was placed in the model as shown in Plate 4. The stability of this plan was tested with normal upper pool, an 8-ft gate opening, and tailwater el of 635.4, and it remained stable. A test was then conducted with the maximum gate opening, 18 ft, and normal tailwater elevation (642.1), and the plan was stable for this condition.

12. A series of tests with single-gate operations was then conducted to determine the range of flow conditions where the type 1 riprap plan remained stable (safe operating range). The model was operated for 1 hour (an equivalent of 5 hours prototype time), drained, and observed to determine if any of

the stones had been displaced during the test. Test results presented in Plate 5 show the stability curve for the type 1 riprap plan. The curve indicates the tailwater for each gate opening at which the riprap began to move. Velocity data obtained for an 8-ft gate opening with a normal tailwater el of 635.4 and with the minimum tailwater for stability with the type 1 riprap plan (el 626.3) are shown in Plates 6 and 7, respectively. Velocity data obtained for 10- and 12-ft gate openings with normal and minimum tailwater for stability of the type 1 riprap plan are shown in Plates 8-11. The velocities along the bottom of the channel increased considerably with the lower tailwaters and continued operations with this type condition will cause excessive scour of the downstream channel.

13. Flow conditions for an 8-ft gate opening with a tailwater elevation of 626.3 (minimum tailwater for stability with the type 1 riprap plan) are shown in Photo 2. Flow conditions shown in Photo 3 with the normal tailwater elevation of 635.4 for an 8-ft gate opening are not nearly as turbulent as for a 626.3 tailwater.

14. The type 1 riprap was replaced with stones with average diameters ranging from 4 to 6 ft, type 2 riprap plan, Plate 12, to determine if operations with tailwater elevations below those shown as stable for the type 1 riprap plan in Plate 5 would be possible. A stability curve for the type 2 riprap plan shown in Plate 5 indicated that gate operations with tailwater elevations lower than those observed with the type 1 riprap plan were possible without failure of the type 2 riprap plan. The type 2 riprap plan was stable for operations with gate openings equal to and less than 10 ft with the minimum project tailwater elevation of 623. As stated previously, gate openings larger than 5 ft with minimum tailwater caused the flow to spray off the baffle blocks which created very unsatisfactory flow conditions immediately downstream of the dam. Velocities measured with uncontrolled flow and a normal tailwater el of 643.3 are shown in Plate 13, and with uncontrolled flow and the minimum tailwater for stability with the type 2 riprap plan, el 634, in Plate 14. The highest velocities observed are shown in Plate 14 and are indicative of the considerable turbulence caused by this flow condition. A velocity of 22 ft/sec was measured over the end sill and velocities up to 12 ft/sec were measured just above the streambed downstream from the stone protection.

15. Center-line sand scour profiles were obtained to compare the extent

of the scour in the exit channel after 5 hours (prototype) of operation with a normal upper pool, an 8-ft gate opening and tailwater elevations of 626.3 and 635.4. The results are shown in Plates 15 and 16, respectively. Test results indicated that the overall scour caused by the lower tailwater, Plate 15, was more severe than the scour that resulted from operations with the normal tailwater, Plate 16. However, neither profile indicated excessive scour in the model.

16. Flow conditions with the minimum tailwater elevation (634) where the type 2 riprap plan remained stable with uncontrolled flow through one gate bay are shown in Photo 4. Photographs of the scour in the exit channel after 5 hours (prototype) of operation with these conditions are shown in Photo 5 and a center-line scour profile is shown in Plate 17. Although the type 2 riprap plan was considered stable with uncontrolled flow and a tailwater elevation of 634, this operation should be avoided, if possible, due to the extreme amount of turbulence observed. Uncontrolled flow with a normal tailwater, el 643.3, is shown in Photo 6 for comparison of turbulence with the two flow conditions.

17. Previous model studies have shown that severe scour and occasionally failure of the riprap blanket occur with an undulating jet exiting the stilling basin. This flow condition occurs for large gate openings with high tailwater. The most severe condition where an undulating jet formed with the submergible gate and stilling basin for the Pike Island model was a 14-ft gate opening and tailwater elevation of 636.0. Photographs of scour in the exit channel after 5 hours (prototype) of operation with the undulating jet flow condition, are shown in Photo 7 and a center-line scour profile is shown in Plate 18. Considerable scour occurred in the exit channel, but the type 2 riprap plan was stable because the stones located on the upper portion of the blanket were not displaced. Displacement at the toe occurred due to undermining of the stone, and sufficient toe protection should eliminate this.

18. Model tests had revealed that an 8-ft gate opening was the minimum gate opening that would pass ice adequately. The type 1 riprap was suitable for ice passage only if tailwater elevations higher than 626.3 exist. If gate openings larger than 8 ft are needed, the tailwater elevation should be at least as high as those shown in Plate 5. Ice can be passed with the minimum project tailwater, el 623, for gate openings up to 10 ft if the type 2 riprap plan is adopted. If uncontrolled flow is allowed, the tailwater must be at

least 634 and the type 2 riprap plan must be used.

19. Additional tests were conducted to determine the stability of the 4- to 6-ft-diameter stones in the type 2 riprap plan placed as a level blanket downstream from the stilling basin. This type placement is designated the type 2 riprap placed horizontally and is shown in Photo 8. A riprap stability curve was developed for the type 2 riprap placed horizontally and is shown in Plate 5. The level blanket of 4- to 6-ft-diameter stones was not as stable as the same diameter stones placed on a 1V on 3H downward slope. The type 2 riprap placed horizontally was not as stable as the type 1 riprap (placed on a 1V on 3H downward slope) for gate openings greater than 11 ft.

20. Photographs of scour in the exit channel after 5 hours (prototype) of operation with uncontrolled flow and a tailwater elevation of 634 with the type 2 riprap placed horizontally are shown in Photo 9. Some of the stones in the blanket upstream from the toe were displaced and this was considered failure. A center-line scour profile obtained after 5 hours (prototype) of operation with uncontrolled flow and a tailwater elevation of 637 (the minimum tailwater elevation where the type 2 riprap placed horizontally remained stable) is shown in Plate 19. The stones at the end of the blanket were undermined and rolled downstream, but this was not considered failure since toe protection could prevent this type of displacement. The most severe scour observed downstream of the level blanket of type 2 riprap was caused by an undulating jet exiting the stilling basin. This occurred with a 14-ft gate opening and a tailwater elevation of 636. Photographs of the scour in the exit channel after 5 hours (prototype) of operation with the undulating jet exiting the stilling basin are shown in Photo 10 and a center-line scour profile after the test is shown in Plate 20. Erosion at the end of the blanket was severe, but the riprap was considered stable because it was not displaced by the flow. Again, a properly designed toe would remain intact. Photographs of scour in the exit channel after 5 hours (prototype) of operation with normal upper pool, an 8-ft gate opening, and a tailwater elevation of 623 (minimum) are shown in Photo 11 for the type 2 riprap placed horizontally and a center-line scour profile obtained after this test is shown in Plate 21. The type 2 riprap placed horizontally was unstable. Although the scour in the exit channel was not extremely severe, some of the stones were displaced slightly. The tailwater should be at least el 624, as shown in Plate 5, for operations with an 8-ft gate opening.

21. ORP requested that a 1V on 2H downward slope be tested to observe the stability of the type 2 riprap placed in this manner. Tests were conducted for the most severe conditions where the type 2 riprap placed on a 1V on 3H downward slope had been stable. These conditions were uncontrolled flow with a tailwater elevation of 634 and a 14-ft gate opening with a tailwater elevation of 634. Center-line scour profiles for these two conditions are shown in Plates 22 and 23, respectively. The riprap did not fail and the scour in the exit channel was not excessive, but due to the uncertainty and lack of control when placing riprap underwater, a 1V on 2H downward slope is not desirable. A 1V on 3H slope is preferred when working underwater.

22. The type 2 riprap was placed back in the model on a 1V on 3H downward slope for additional testing with flow through more than one gate. A test was conducted for 10 hours (prototype) with two adjacent gates open 8 ft and a tailwater elevation of 626.3. A forced hydraulic jump occurred in the stilling basin and the riprap remained stable. Another test was conducted with two adjacent gates open 8 ft and a tailwater elevation of 623.0. The flow sprayed off the baffle blocks and plunged into the downstream channel, but the riprap remained stable. The type 2 riprap placed on a 1V on 3H slope was considered stable for all conditions indicated as stable on the curve shown in Plate 5.

23. All previous tests had been conducted with the spillway trajectory shape for the submergible gate bay section in the model, see Plate 1. The spillway trajectory shape for the nonsubmergible gate bay section, Plate 1, was installed in the model to determine if flow conditions in these gate bays have an effect on the stability of the riprap. Energy dissipation in the stilling basin was improved with this trajectory shape and scour in the exit channel was less than observed with the trajectory shape for the submergible gate section. An undulating jet did not form with this trajectory shape. It was concluded that riprap placed downstream of the nonsubmergible gate bay sections would remain stable for the same flow conditions where riprap placed downstream of the submergible sections remained stable.

24. The scour protection plan shown in Plate 24 was designed by the ORP to repair the scoured area immediately below the stilling basin. This design was placed in the model and tested to insure the adequacy of the plan. The design differed slightly from the type 2 riprap placed on a 1V on 3H slope in that an additional 14-ft horizontal section of tremie concrete and fabric bag

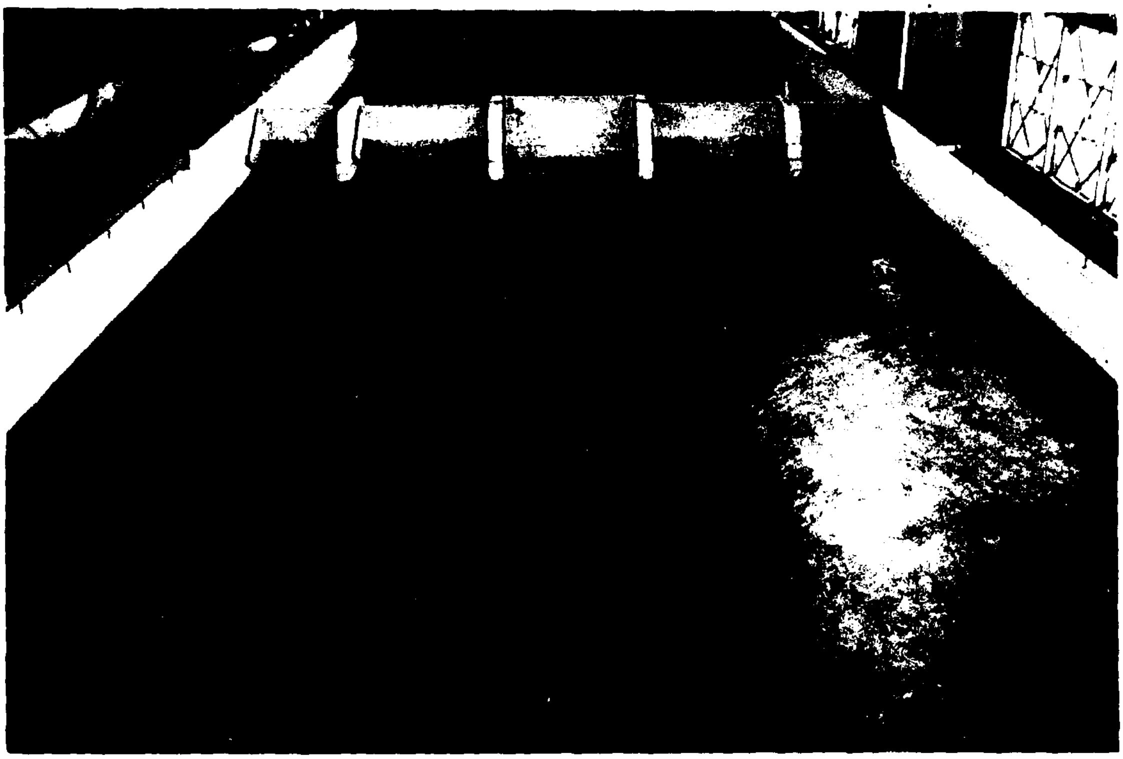
filled with grout was placed downstream of the bulkhead pad. There was concern that this addition might change flow conditions enough to effect the stability of the riprap on the sloped portion of the protection. Also, the riprap in this design had a maximum diameter of 5 ft instead of 6 ft which was equivalent to reducing the weight from 18,662 lbs to 10,800 lbs. All stones previously used for the type 2 riprap that had equivalent weights more than 10,800 lbs were replaced. A test was conducted for 5 hours (prototype) with normal upper pool, an 8-ft gate opening, and a tailwater elevation of 623, and the design remained stable. Another test was conducted for 5 hours (prototype) with normal upper pool, 14-ft gate opening and a tailwater el of 636. Photographs of the scour in the exit channel after the completion of this test are shown in Photo 12. The photograph illustrates the scouring potential of this type flow, but the riprap remained stable. Displacement at the toe occurred due to undermining of the stone, and sufficient toe protection would eliminate this. This design was considered stable for all flow conditions where the type 2 riprap placed on a 1V on 3H slope remained stable.

PART IV: SUMMARY AND RECOMMENDATIONS

25. Model tests to determine a scour protection plan for Pike Island Dam indicated that large riprap could be used to protect the area immediately below the stilling basin, and thus prevent undermining of the structure if appropriate gate operations are followed. A gate opening of 8 ft was determined to be the minimum required to pass ice through the structure. The type 1 riprap plan, Plate 4, did not provide the protection required to pass ice or debris with minimum tailwater. The type 2 riprap (4-6-ft stones) placed on a 1V on 3H slope, as shown in Plate 12, was stable for gate openings up to 10 ft with minimum tailwater. The type 2 riprap placed horizontally, as shown in Photo 8, was not stable for gate openings greater than 6 ft with minimum tailwater. The type 2 riprap placed on slopes milder than a 1V on 3H was not as stable as when placed on a 1V on 3H slope. Slopes steeper than 1V on 3H were not desirable due to the tendency of the stones to roll downstream when placing them underwater.

26. The final design tested, Plate 24, consisted of a short section of tremie concrete and a row of grout-filled fabric bags placed horizontally just downstream of the stilling basin followed with 5-ft-diameter stones placed on a 1V on 3H slope. This plan was stable for the same flows where the type 2 riprap plan placed on a 1V on 3H downward slope remained stable. These conditions are indicated on the stability curve shown in Plate 5. Therefore, this design is recommended to protect the area immediately downstream from the Pike Island Dam stilling basin. The plan provides good granular filters underneath the 5-ft-diameter stones and has additional stone protection at the toe. This plan should not be subjected to conditions indicated as unstable for the type 2 riprap plan (4- to 6-ft-diameter stones placed on a 1V on 3H downward slope) shown in Plate 5. It is also recommended that the area to be repaired be excavated or filled as necessary so that the 5-ft-diameter stones can be placed on a 1V on 3H downward slope. Turbulent flow conditions exist below the stilling basin for gate openings equal to and greater than 8 ft with minimum tailwater. It was beyond the scope of this model study to develop a scour protection plan that could withstand uncontrolled flow and minimum tailwater. It is extremely important that 8- and 10-ft gate openings with a tailwater elevation of 623 be operated for as short a period as possible, and gate openings greater than 10 ft with minimum tailwater never be allowed.

Photo 1. Spray condition; pool el 644, tailwater el 625.3, gate opening 8 ft



a. General view looking upstream

b. Close-up view looking upstream

Photo 2. Flow conditions with an 8-ft gate opening; tailwater el 626.3

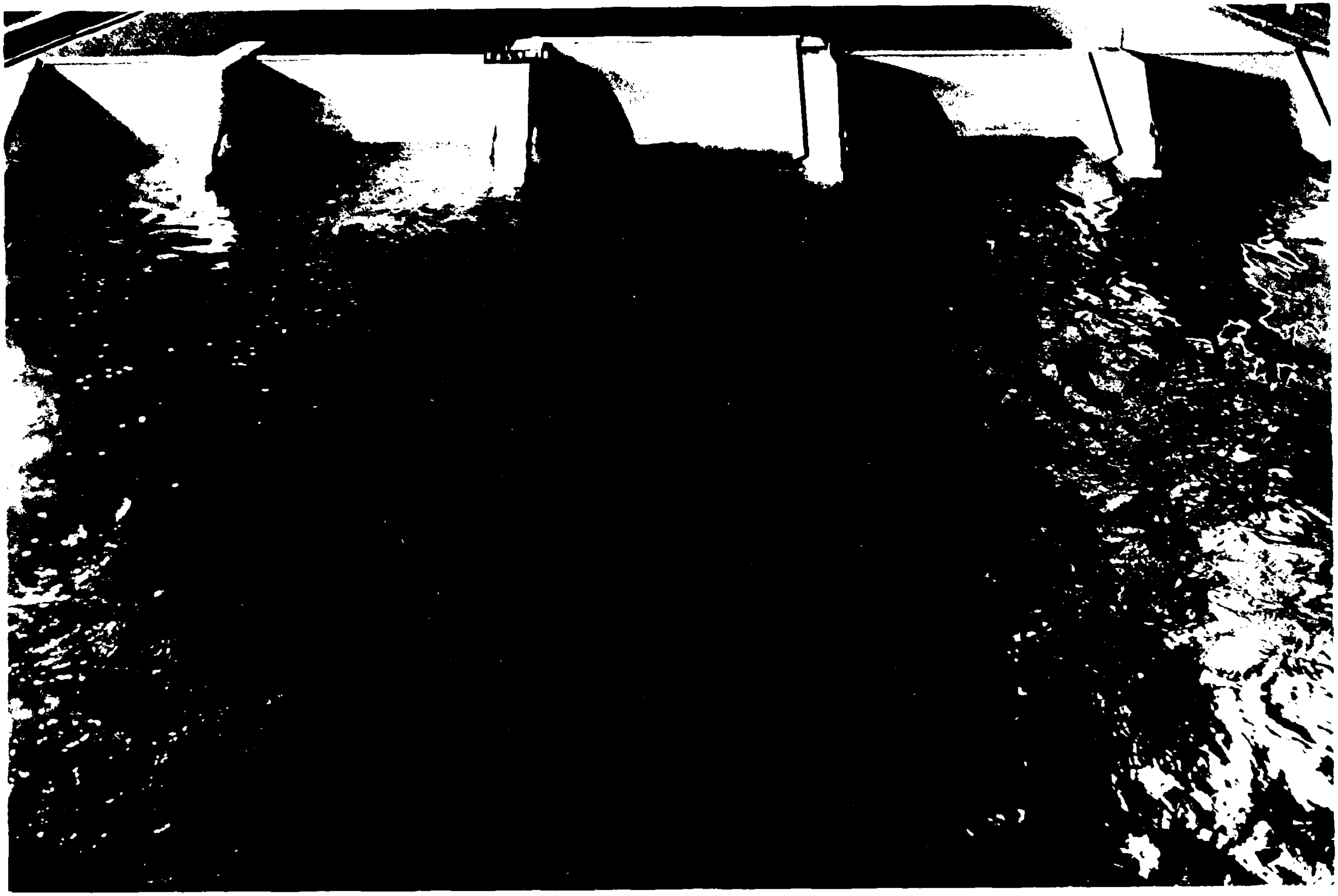
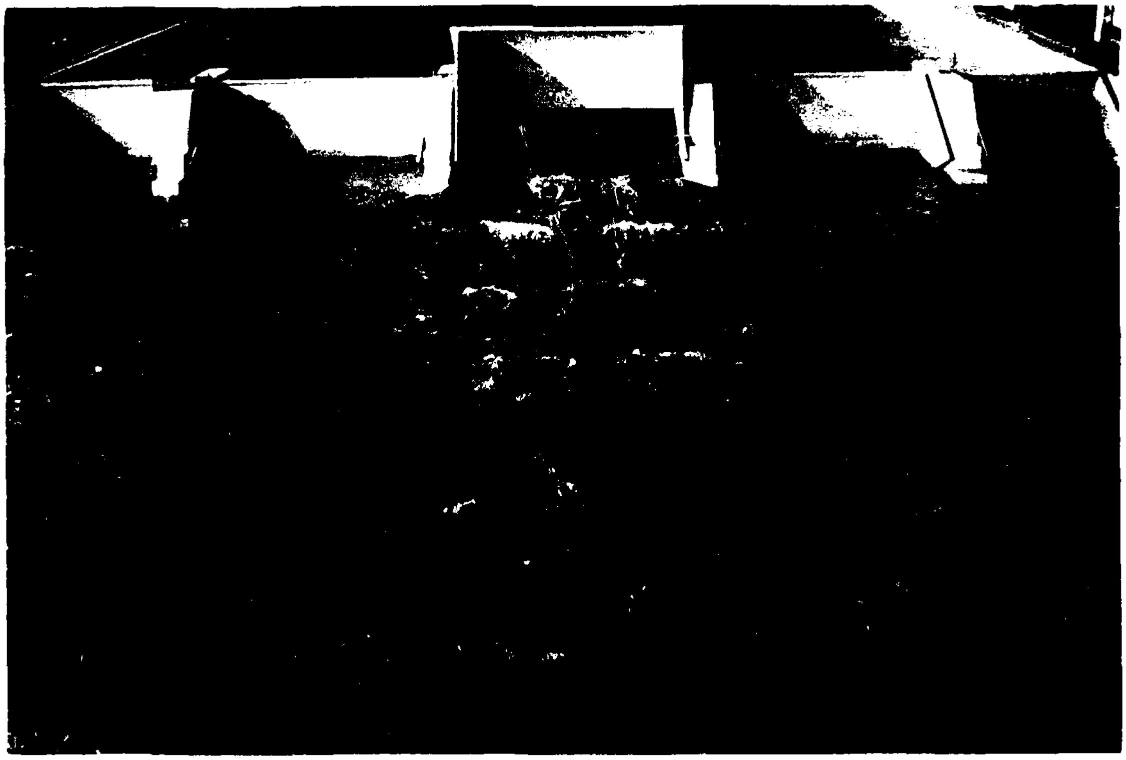


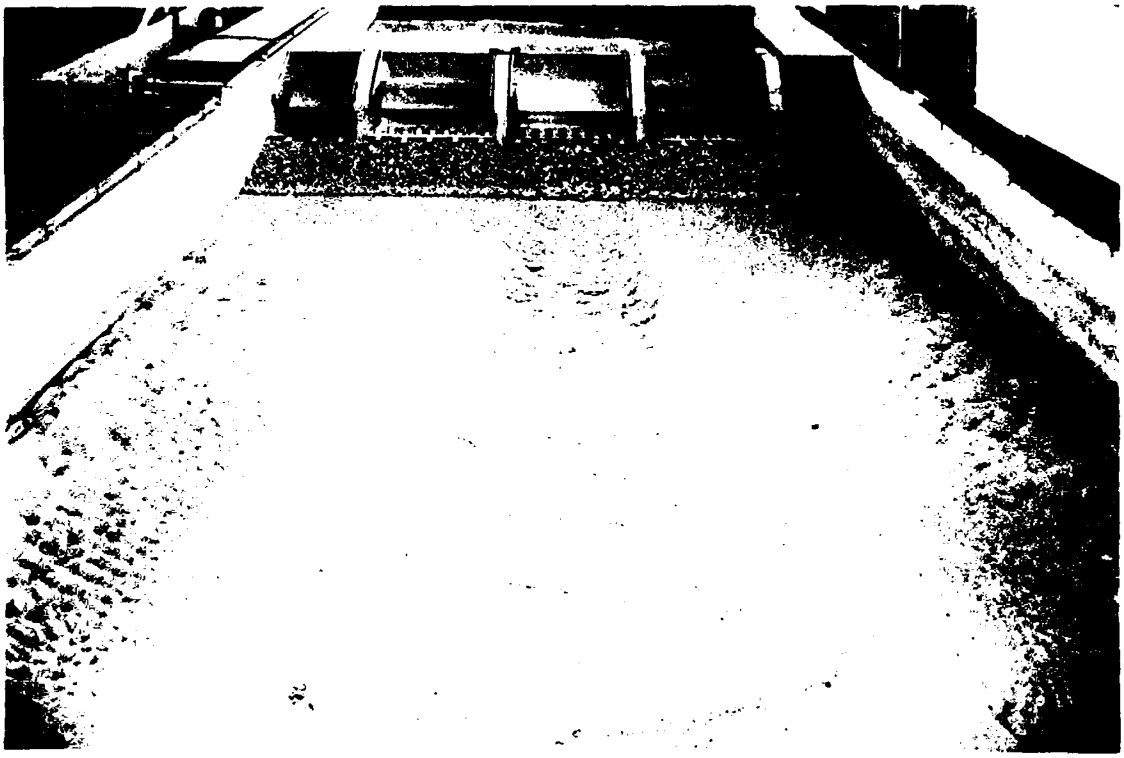
Photo 3. Flow conditions with an 8-ft gate opening;
tailwater el 635.4

a. General view looking upstream

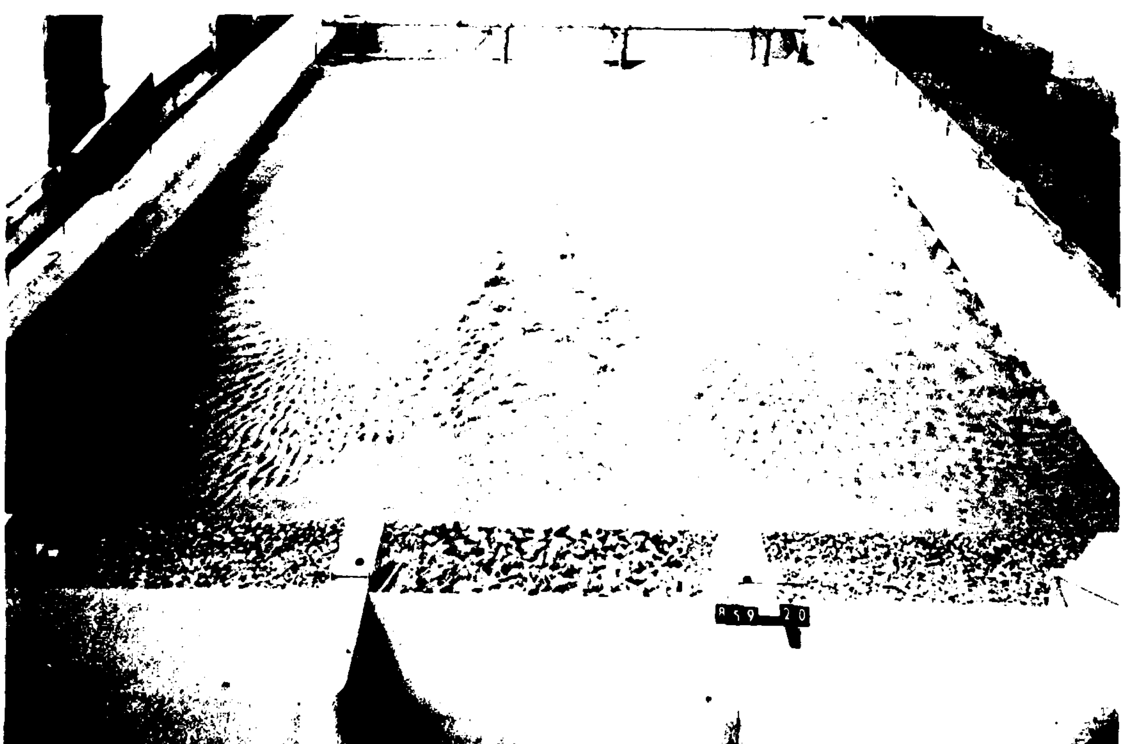


b. Close-up view looking upstream

Photo 4. Uncontrolled flow with type 2 riprap plan;
pool el 644, tailwater el 634



a. Looking upstream



b. Looking downstream

Photo 5. View of scour in exit channel after 5 hr of operation with pool el 644, tailwater el 634, and uncontrolled flow

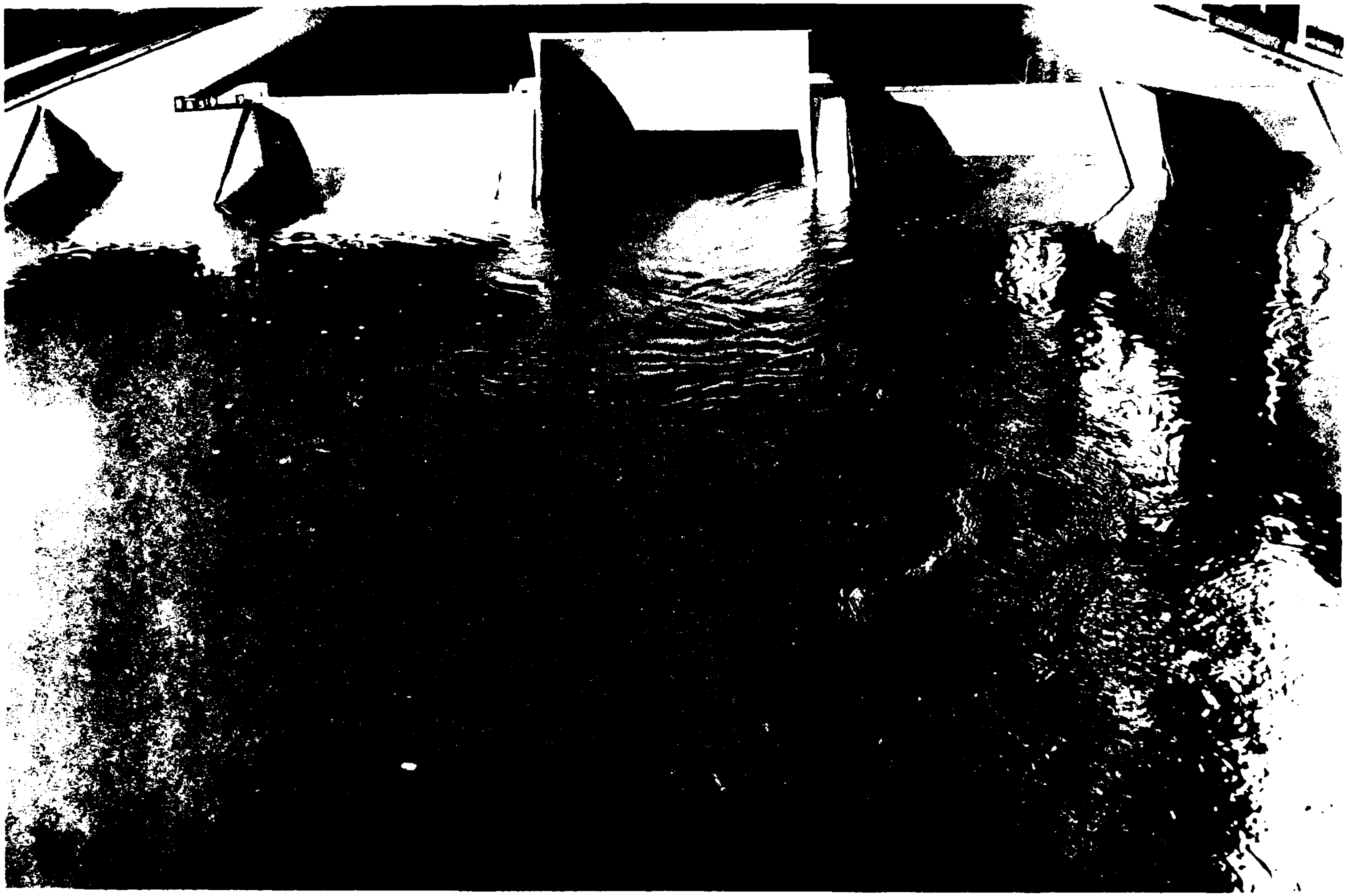
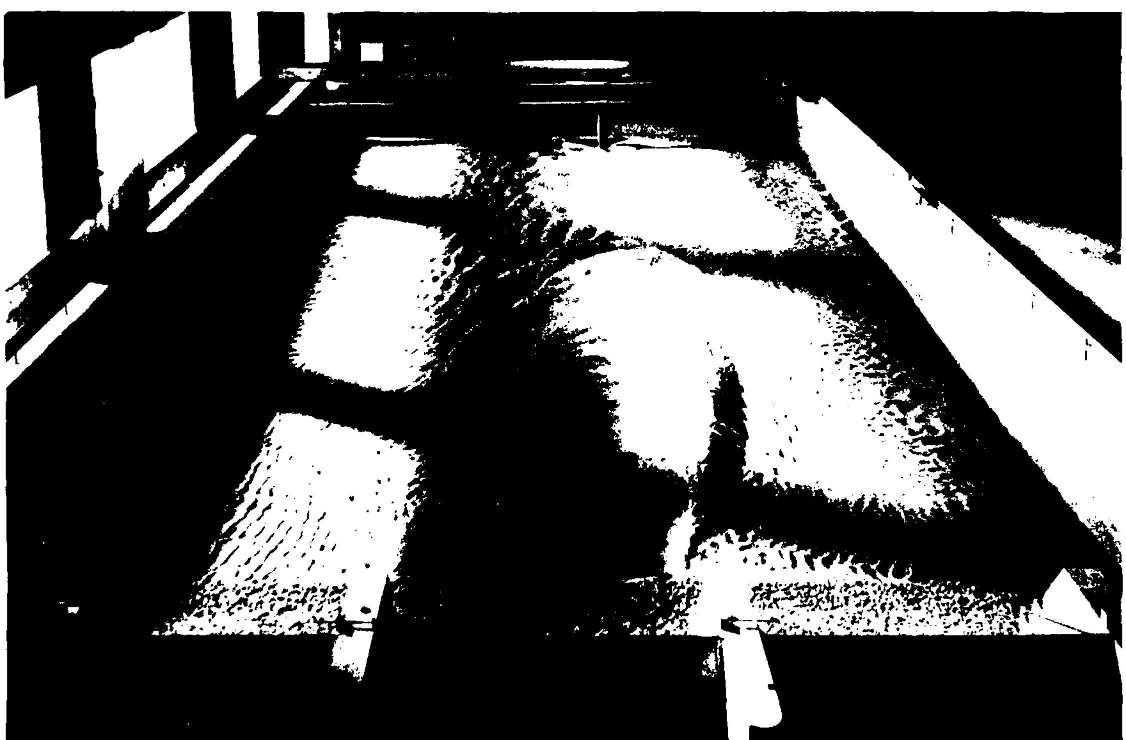


Photo 6. Uncontrolled flow with type 2 riprap plan; pool el 644, tailwater el 643.3

a. Looking upstream

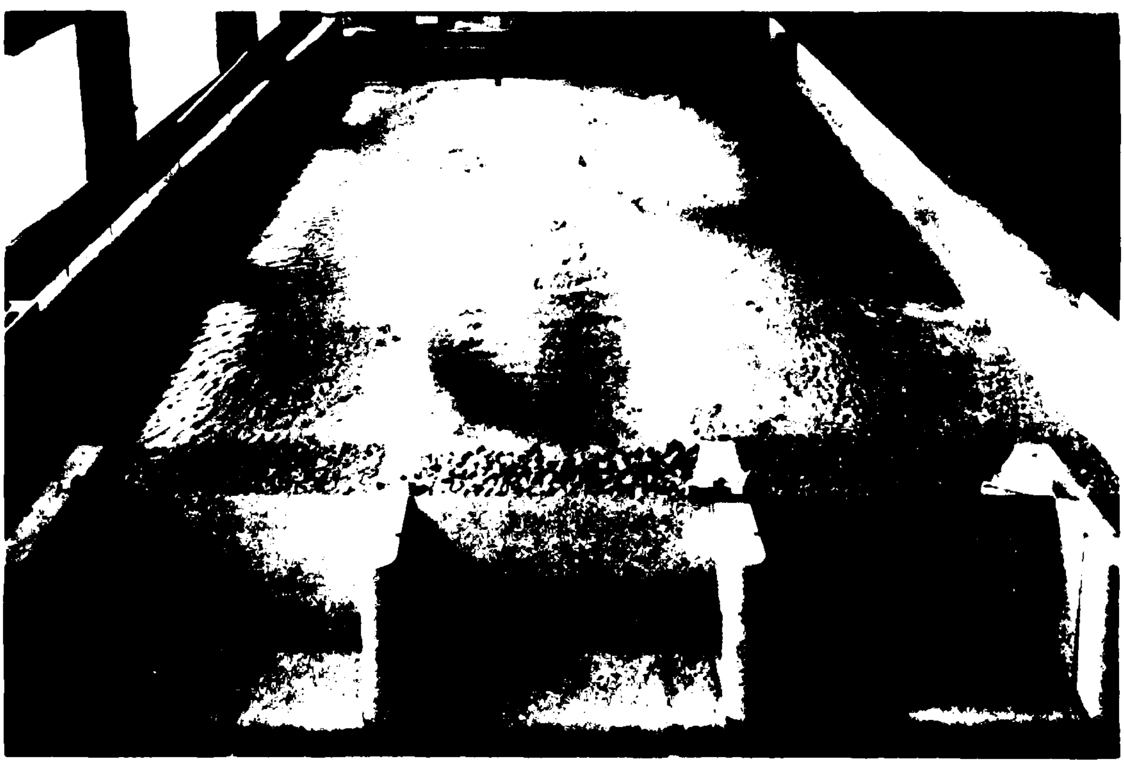


b. Looking downstream

Photo 7. Scour in exit channel after 5 hr of operation with pocl el 644, tailwater el 636.0 and a 14-ft gate opening

Photo 8. Type 2 riprap placed horizontally.

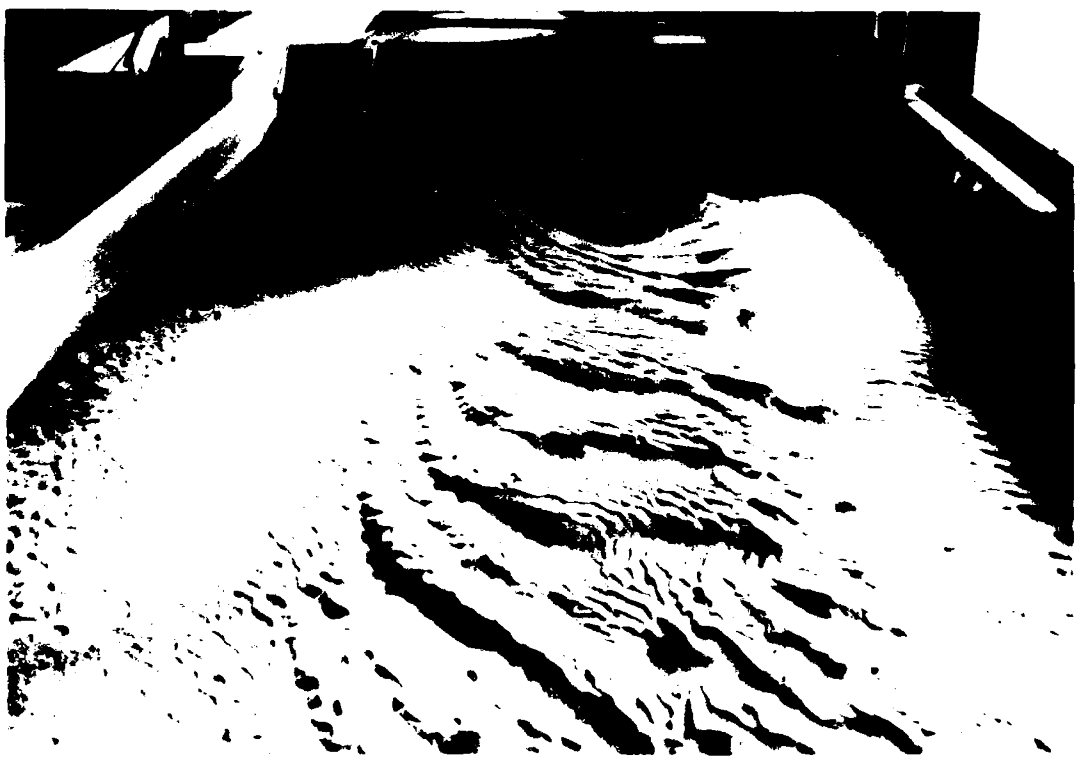
a. Looking upstream



b. Looking downstream

Photo 9. View of scour in exit channel after 5 hr of operation, with pool el 644, tailwater el 634.0, and uncontrolled flow, and the type 2 riprap placed horizontally

a. Looking upstream

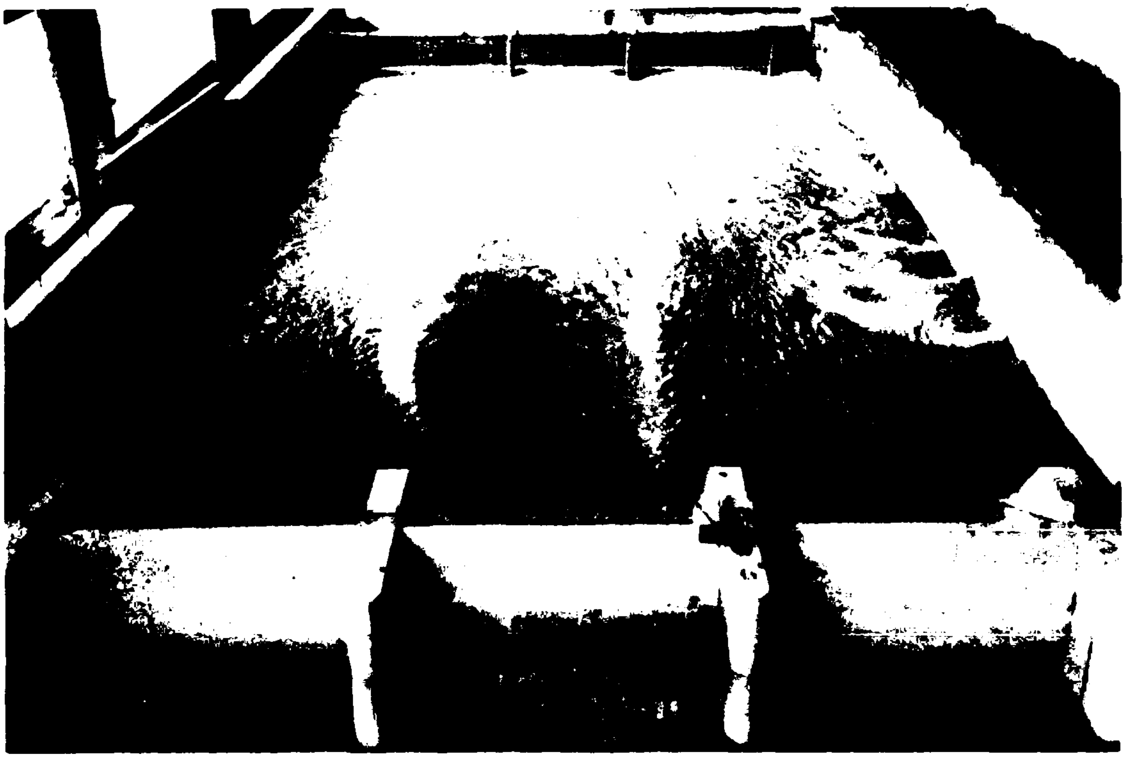


b. Looking downstream

Photo 10. View of scour in exit channel after 5 hr of operation, with pool el 644, tailwater el 636, and a 14-ft gate opening, and the type 2 riprap placed horizontally

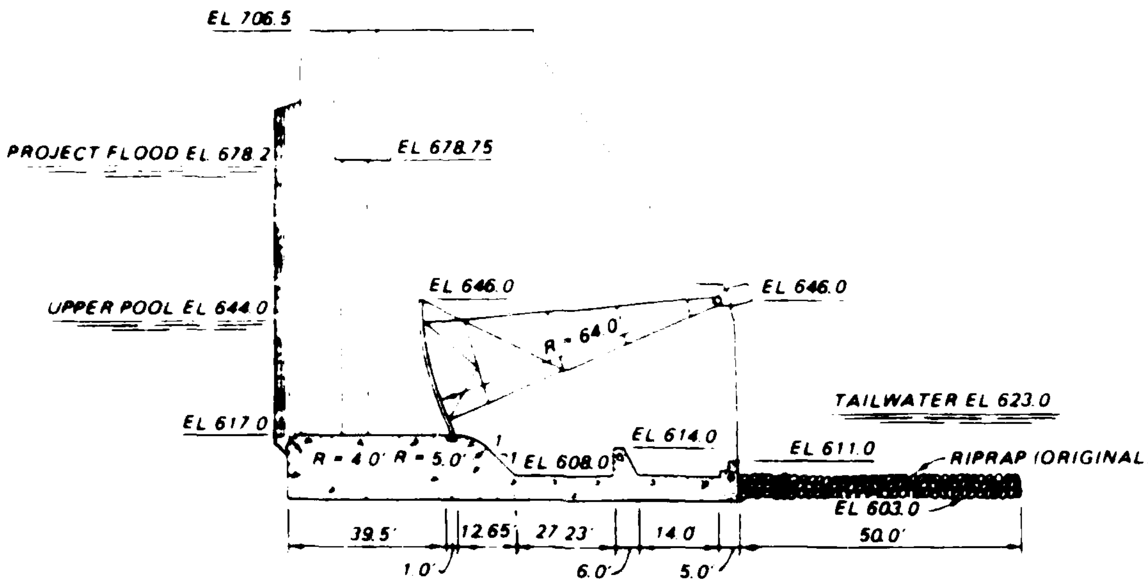
Photo 11. View of scour in exit channel after 5 hr of operation with pool el 644, tailwater el 623, and an 8-ft gate opening and the type 2 riprap placed horizontally

a. Looking upstream

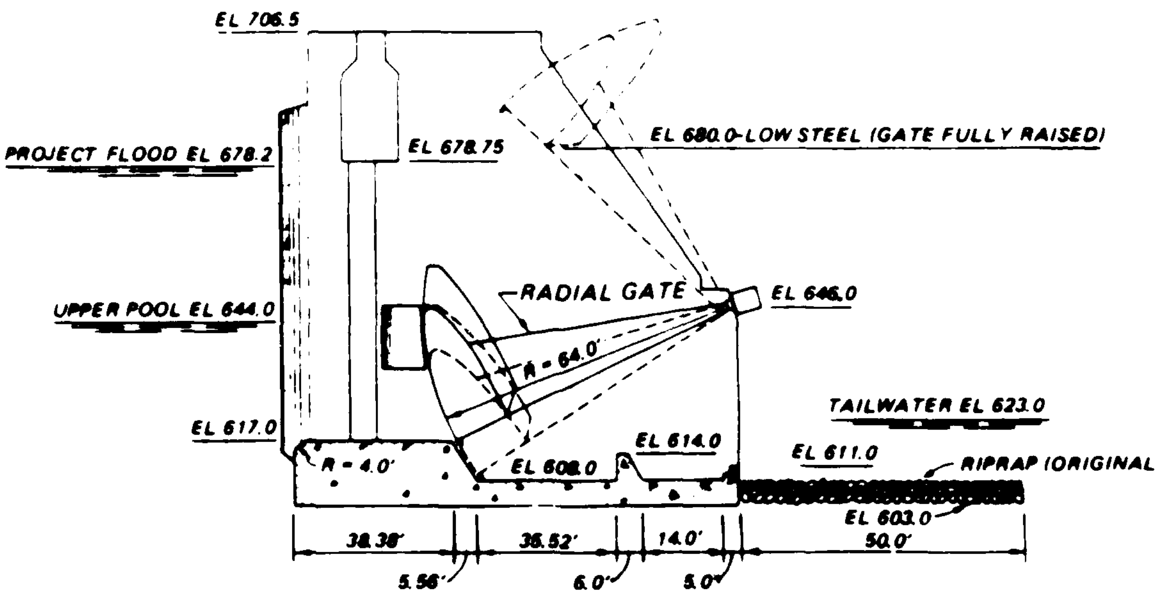


b. Looking downstream

Photo 12. View of scour in exit channel after 5 hr of operation, with pool el 644, tailwater el 636, a 14-ft gate opening and the recommended plan



SECTION THROUGH SPILLWAY - NONSUBMERGIBLE GATE

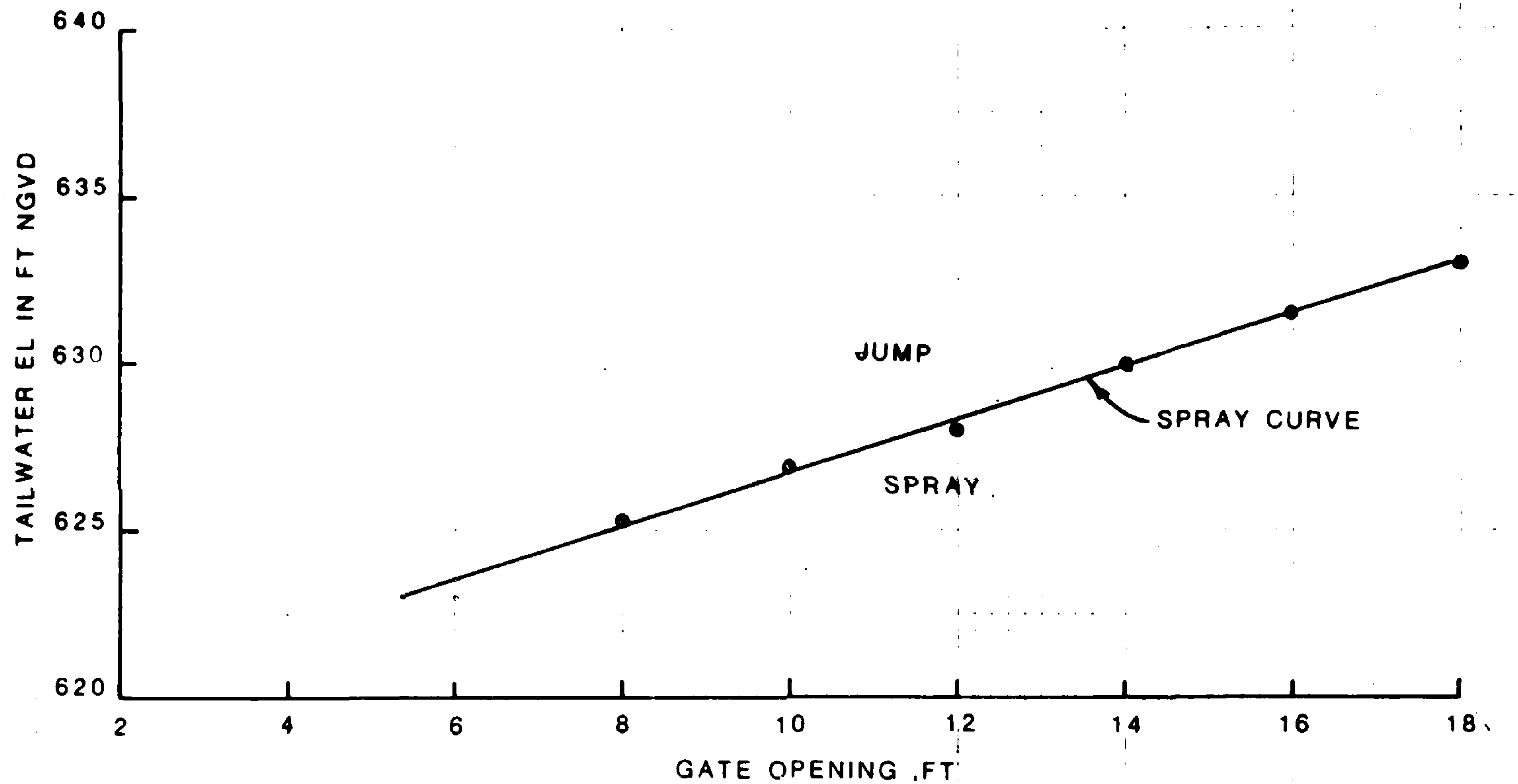


SECTION THROUGH SPILLWAY - SUBMERGIBLE GATE

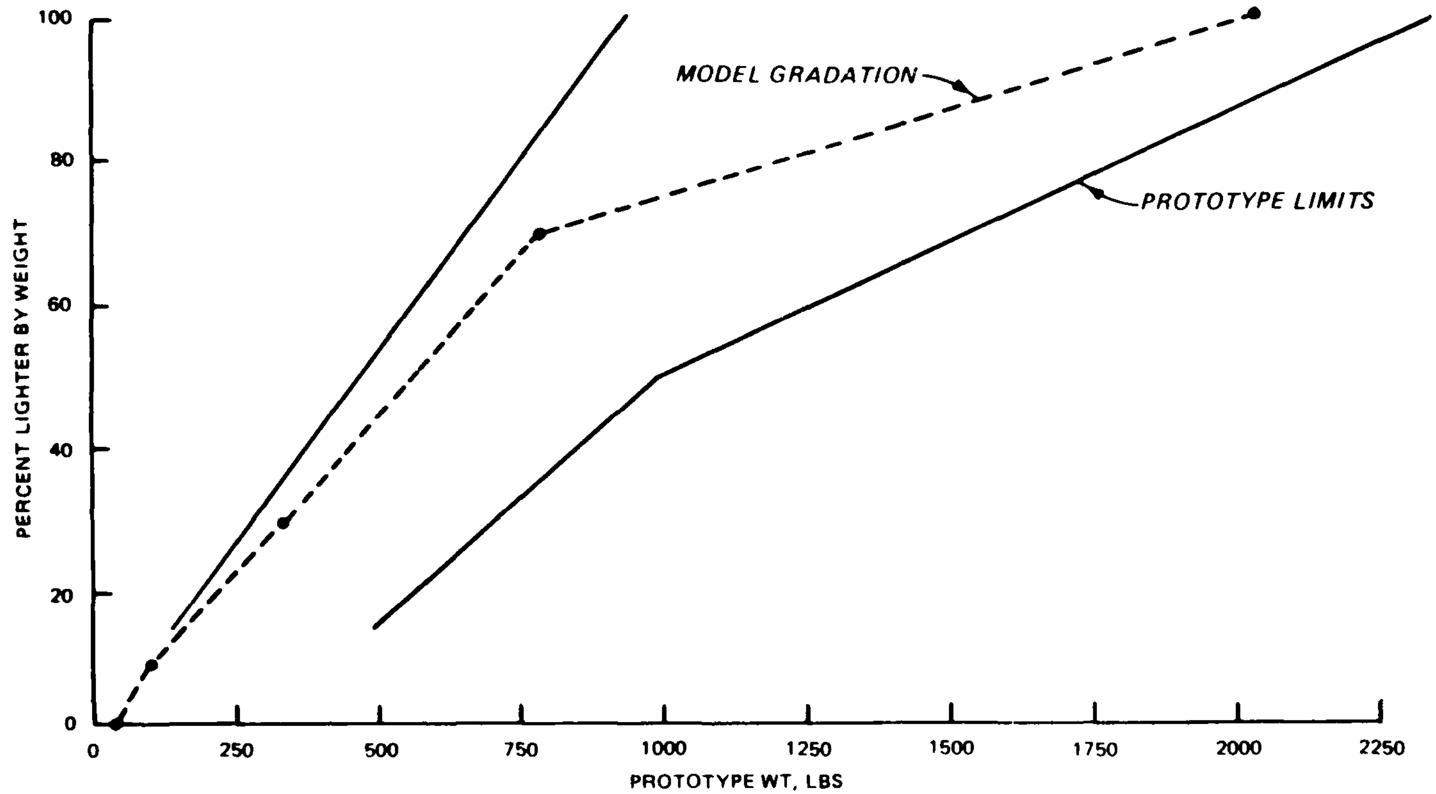
SPILLWAY SECTIONS

NONSUBMERGIBLE AND

SUBMERGIBLE GATES



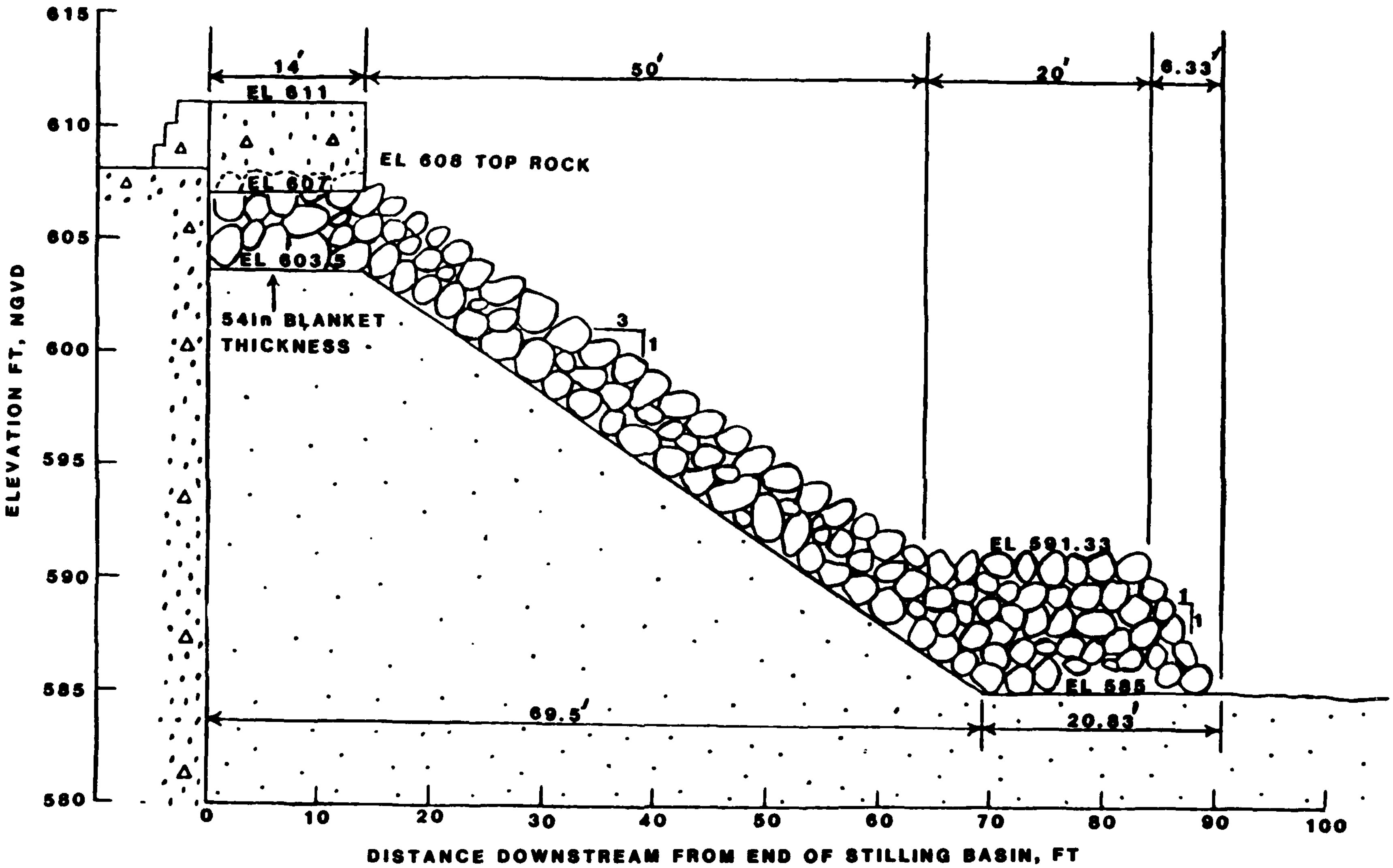
TAILWATER EL vs BASIN ACTION
SUBMERGIBLE GATE
UPPER POOL EL 644



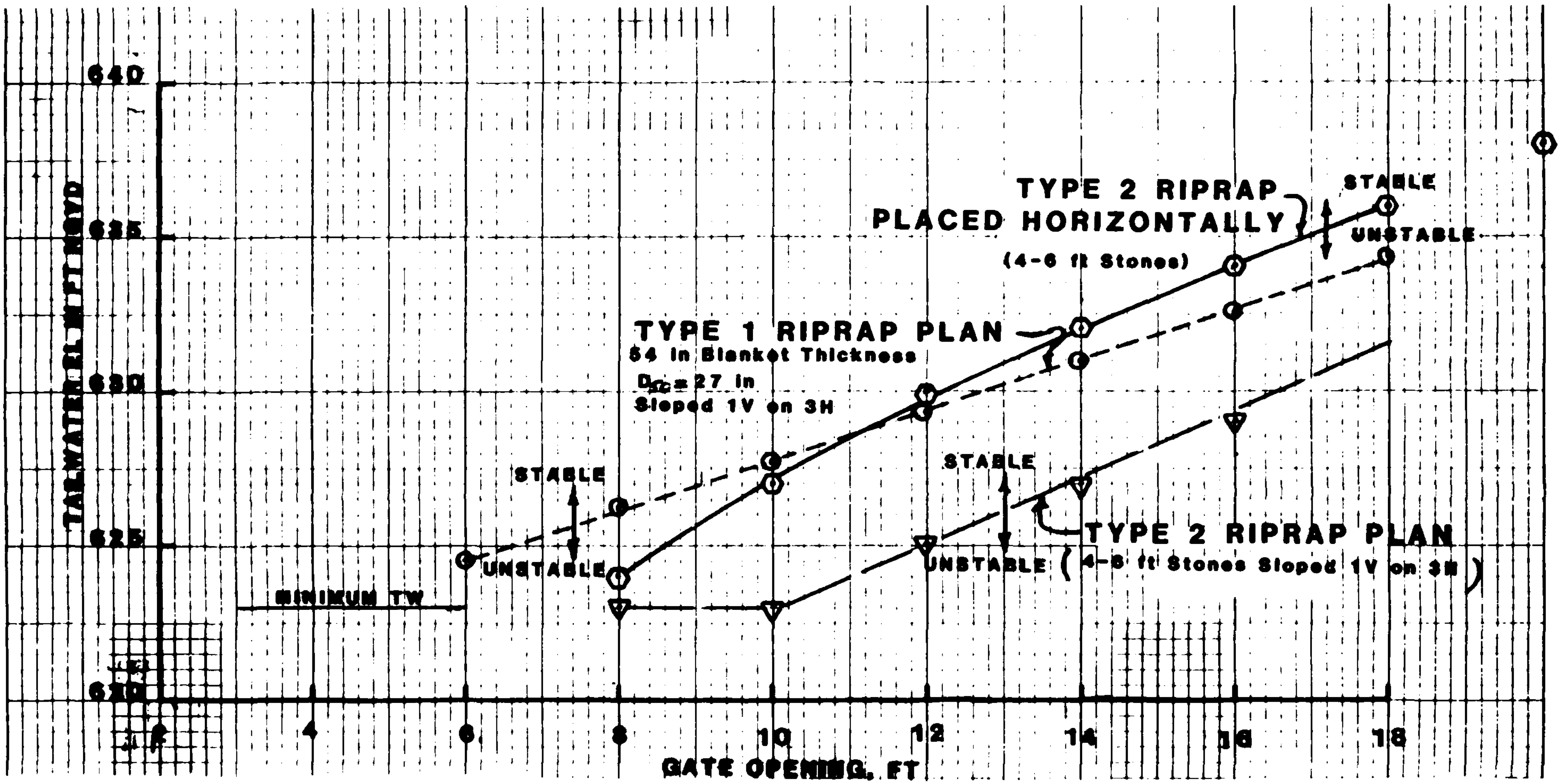
TYPE 1 RIPRAP GRADATION

BLANKET THICKNESS = 54in.

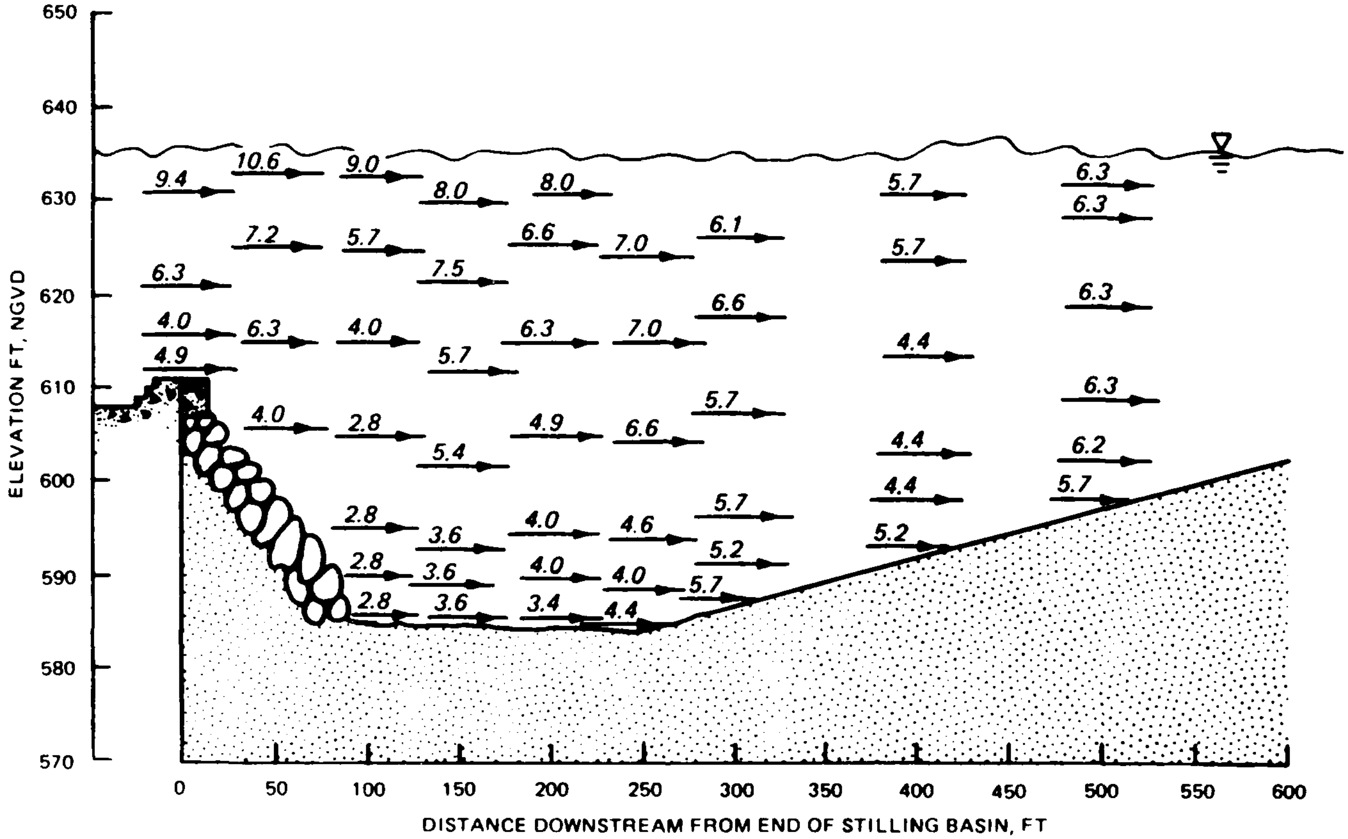
D_{50} = 27in.



TYPE 1 RIPRAP PLAN



STABILITY CURVES
SUBMERGIBLE GATE
UPPER POOL- 644



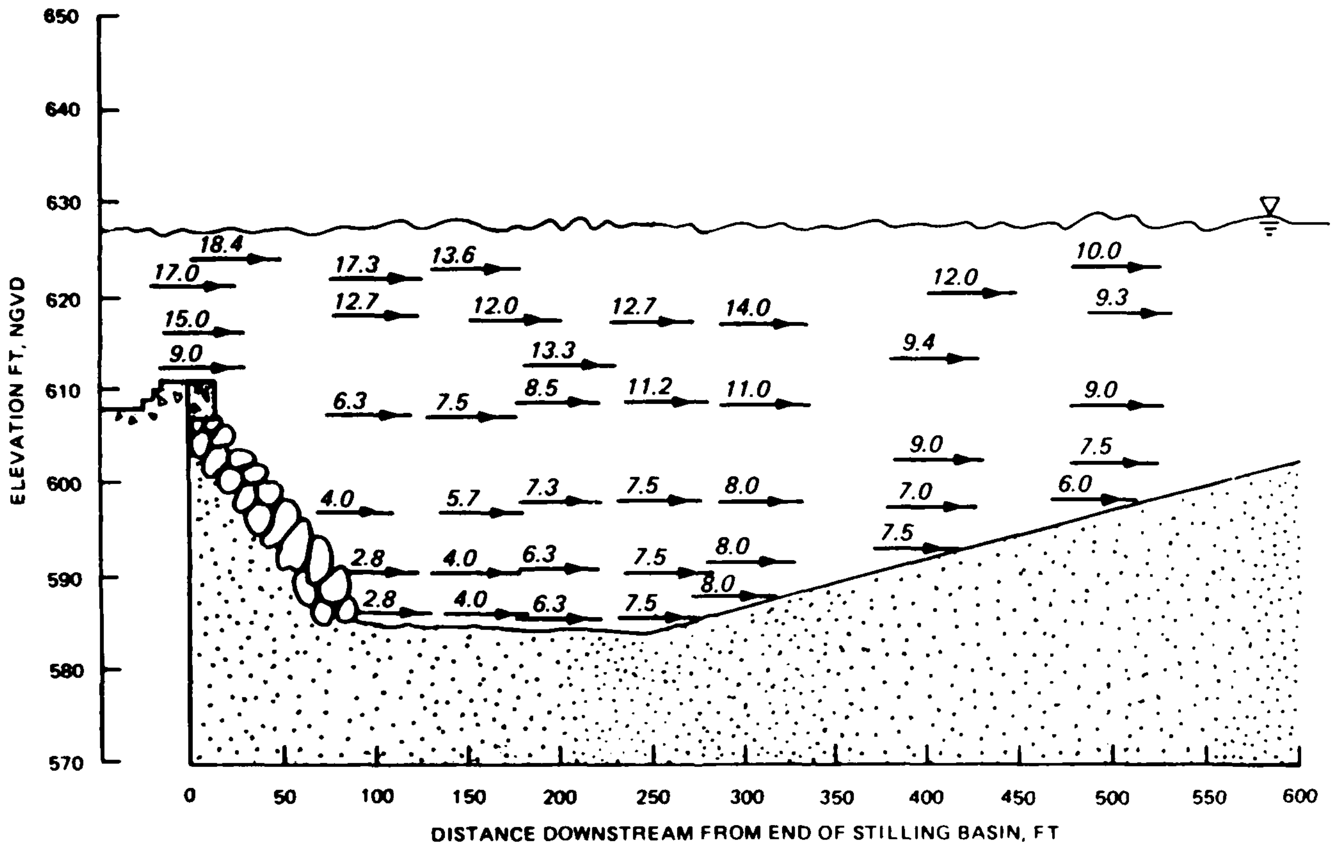
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 635.4

GATE OPENING - 8 FT



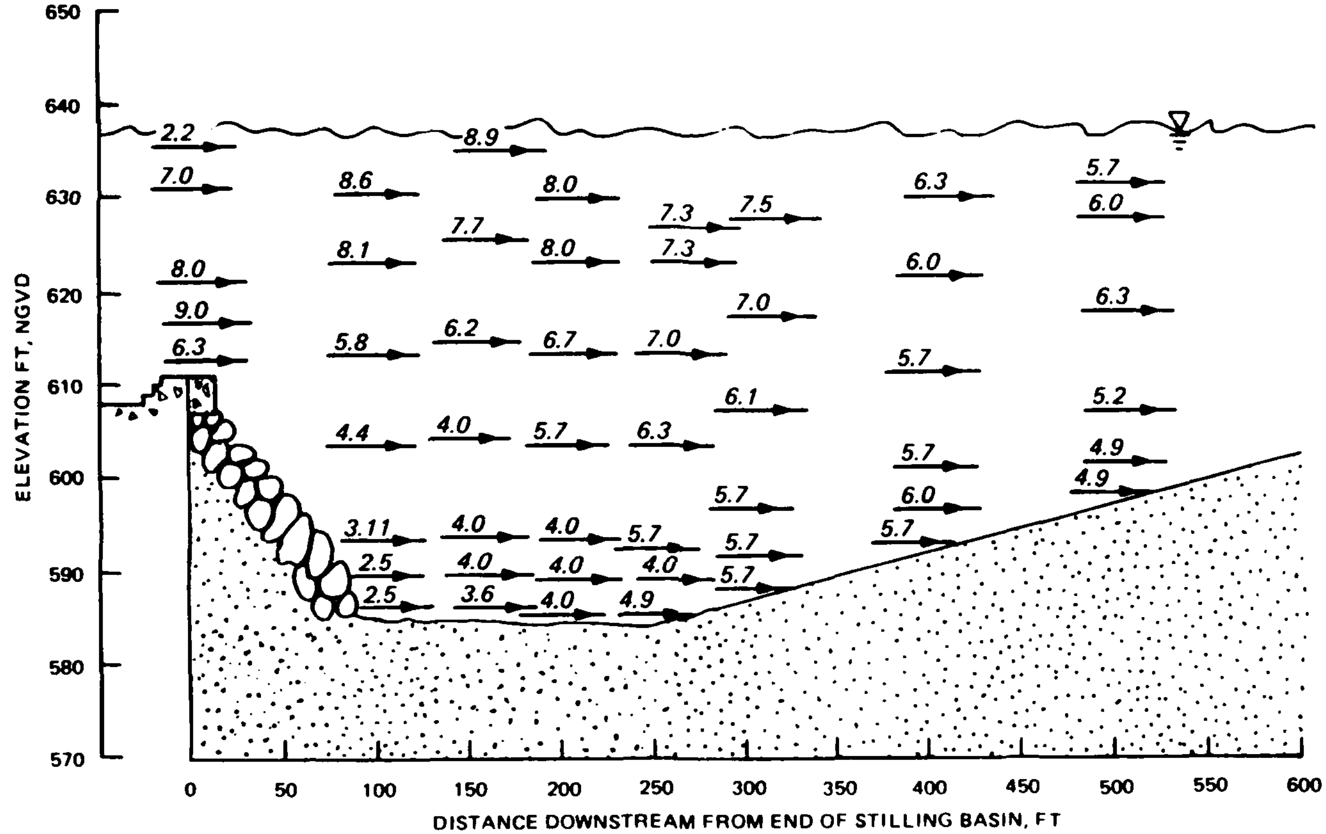
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 626.3

GATE OPENING - 8 FT



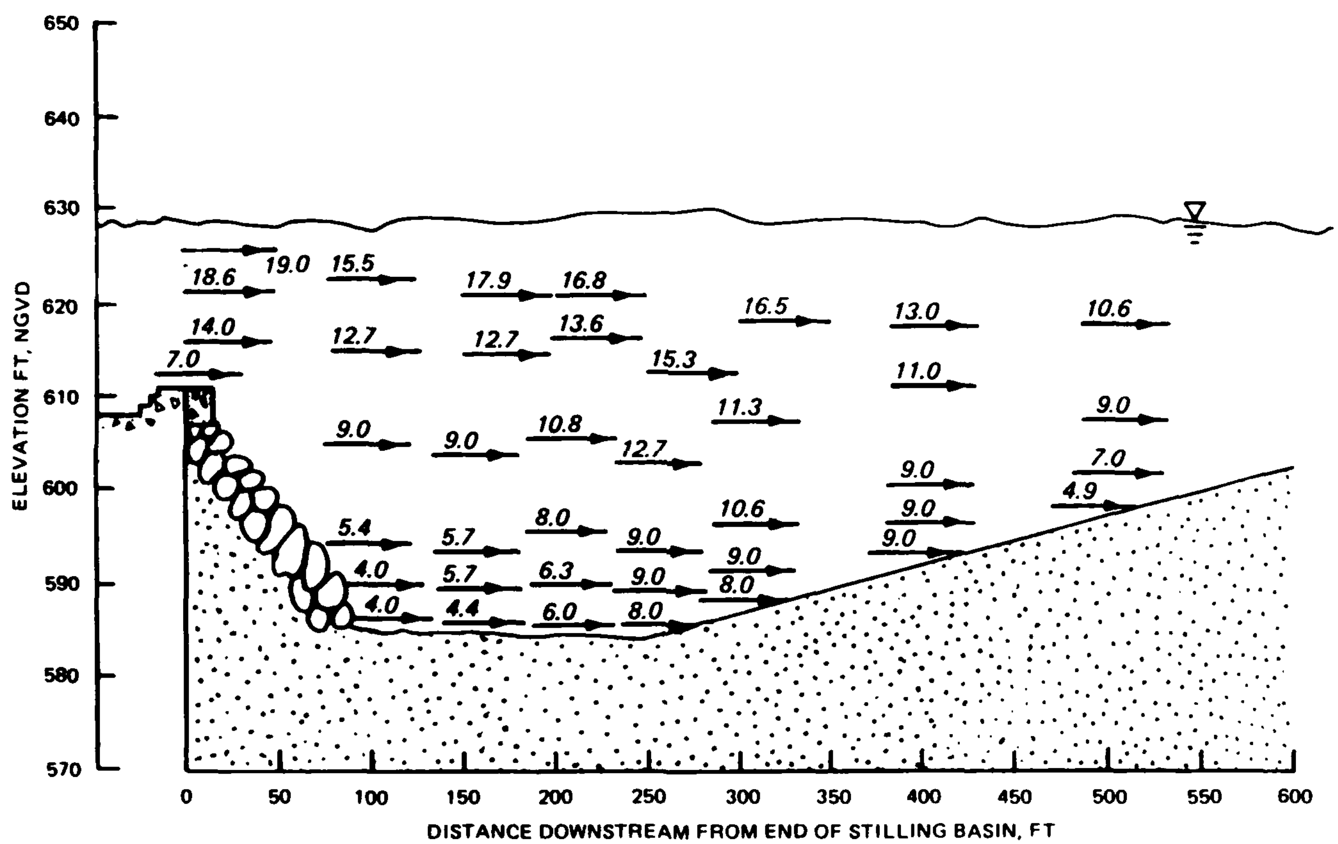
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 637.5

GATE OPENING - 10 FT



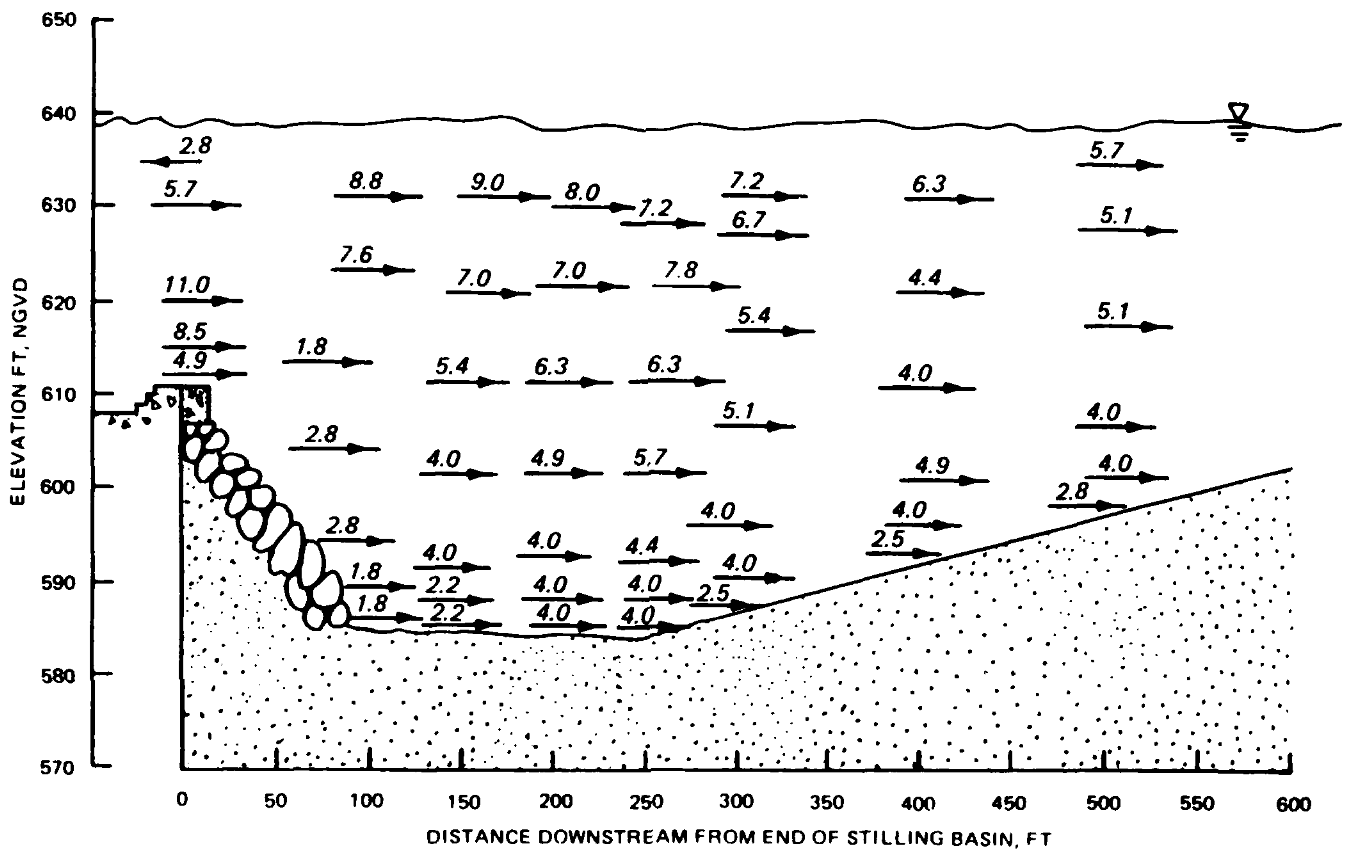
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND
AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 628.0

GATE OPENING - 10 FT



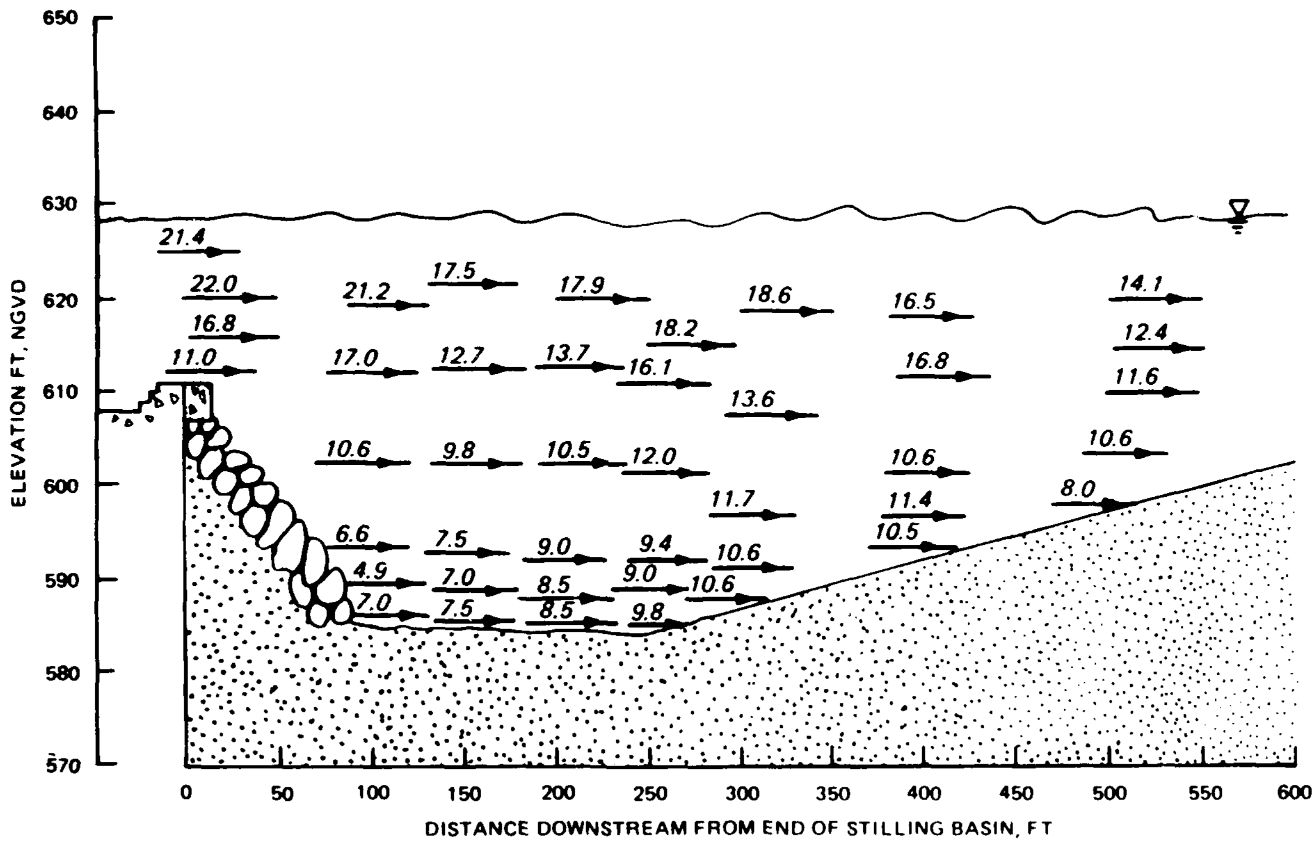
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 639.2

GATE OPENING - 12 FT



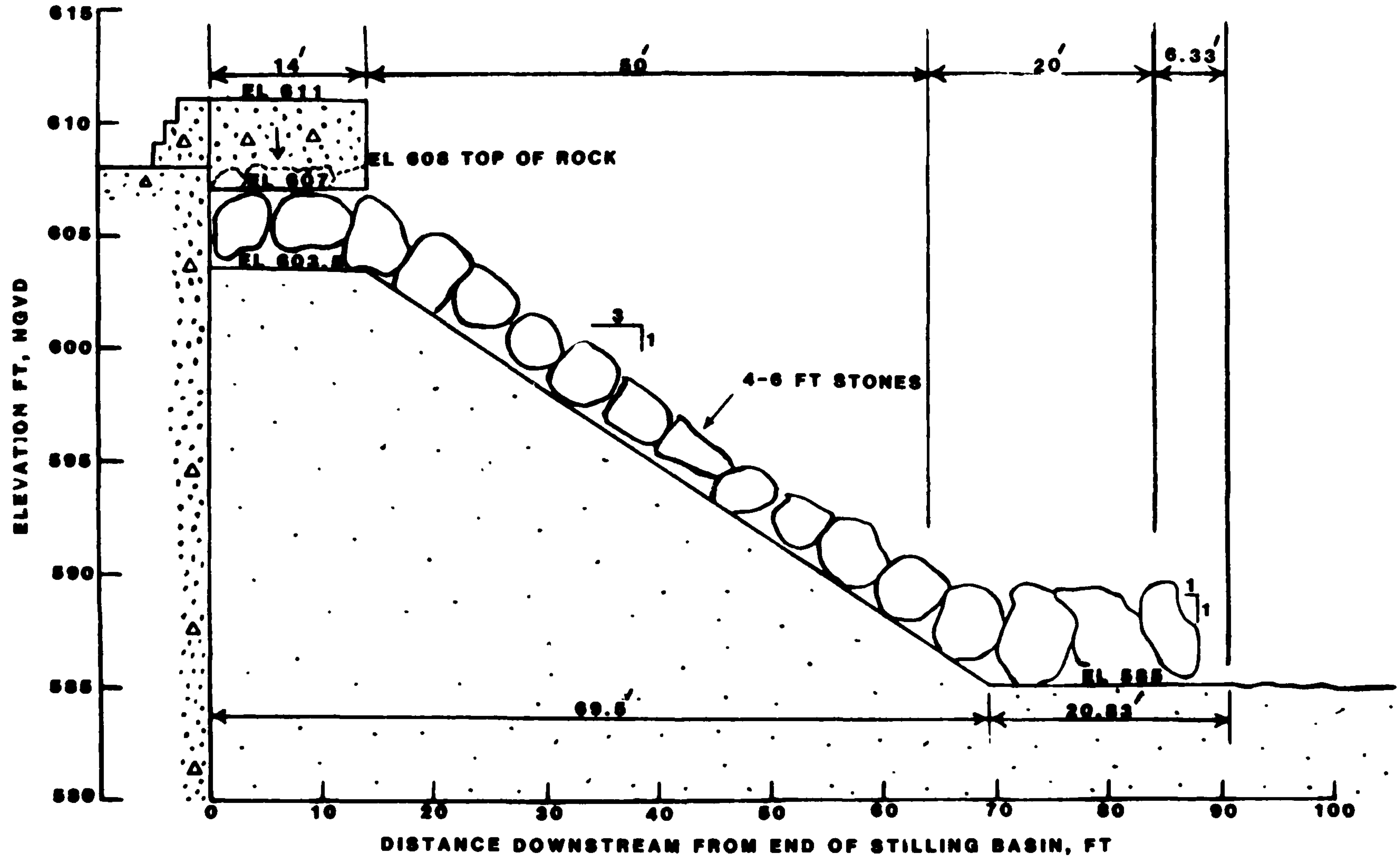
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

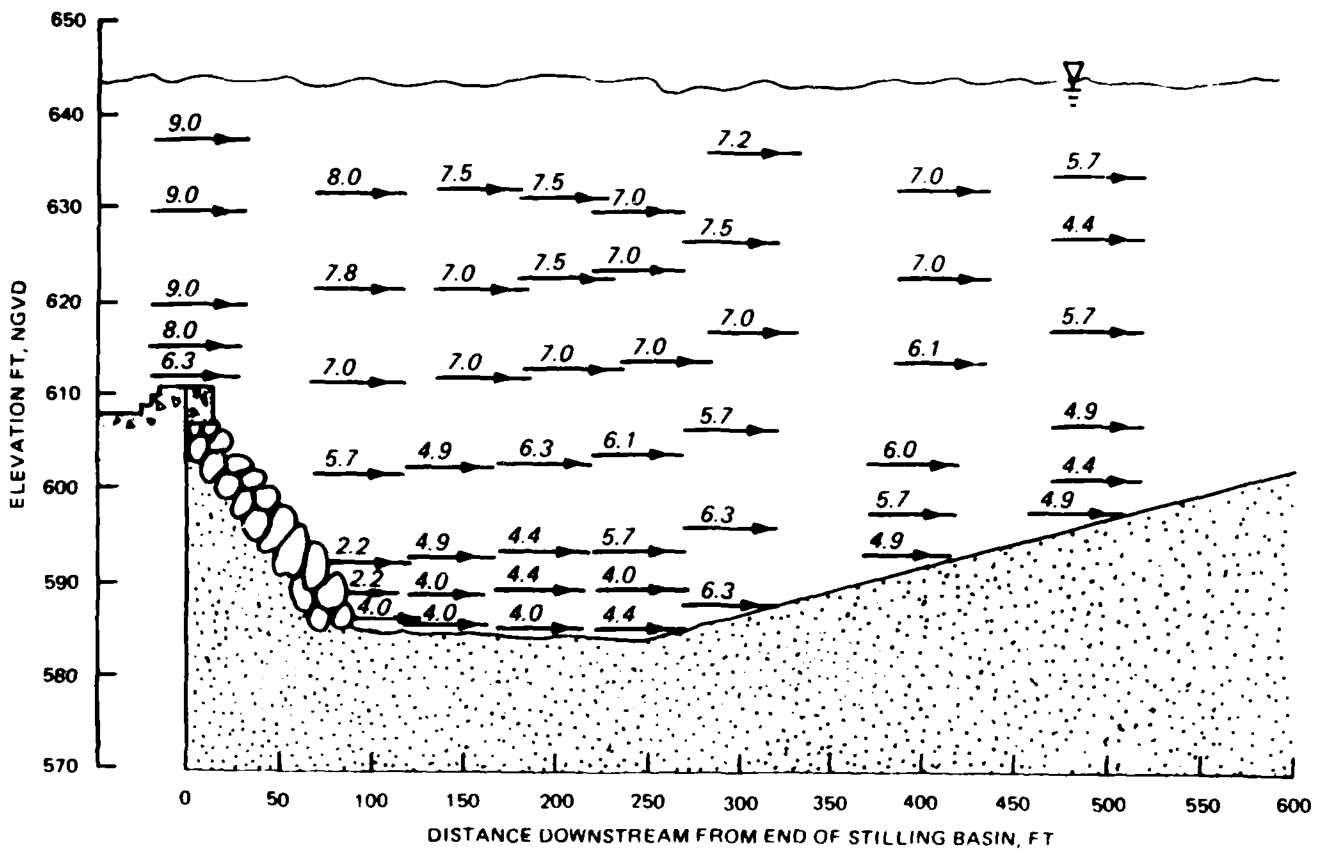
POOL EL - 644

TW EL - 629.0

GATE OPENING - 12 FT



TYPE 2 RIPRAP PLAN



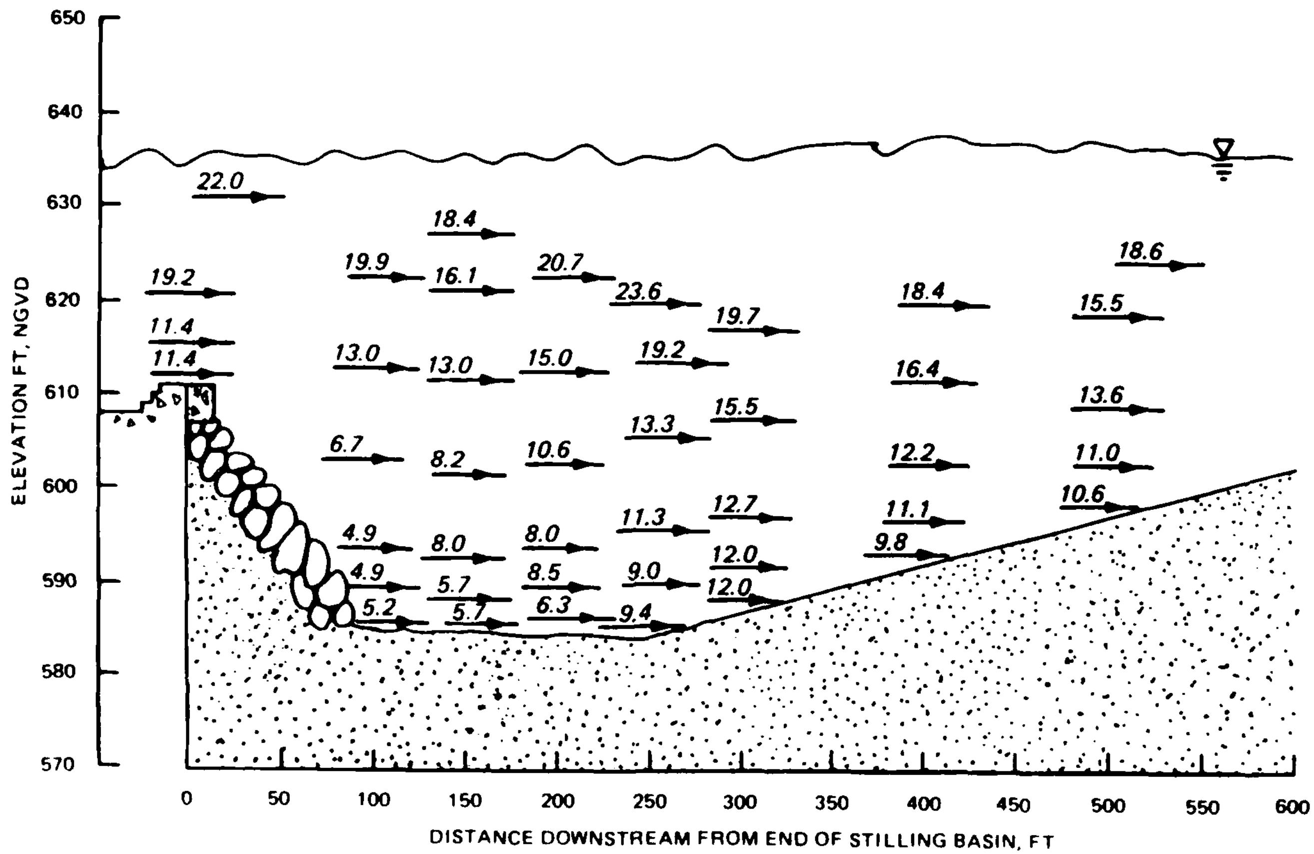
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

TW EL - 643.3

UNCONTROLLED FLOW



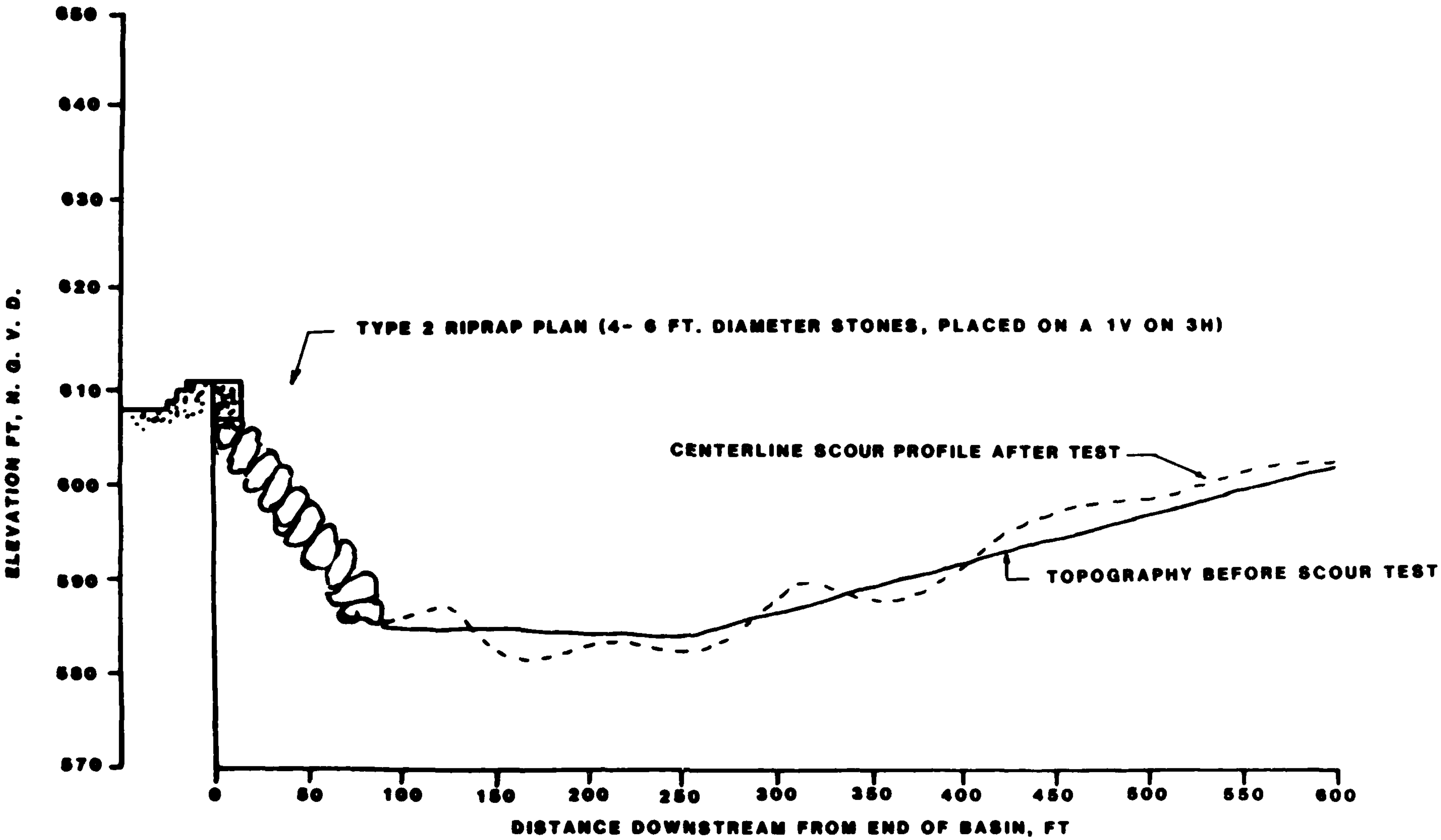
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND TAKEN ALONG MODEL CENTERLINE

VELOCITIES

POOL EL - 644

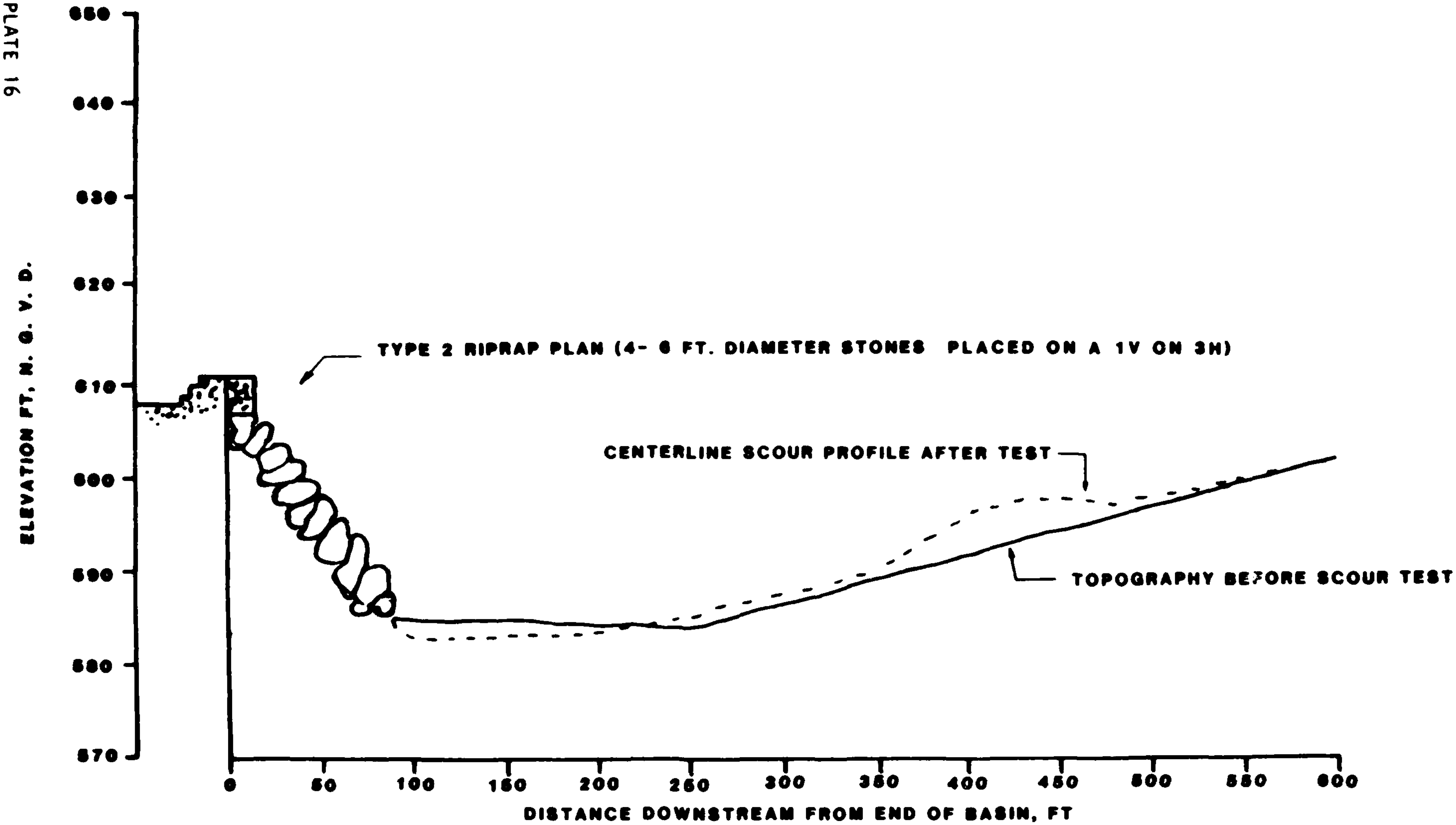
TW EL -634.0

UNCONTROLLED FLOW



NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

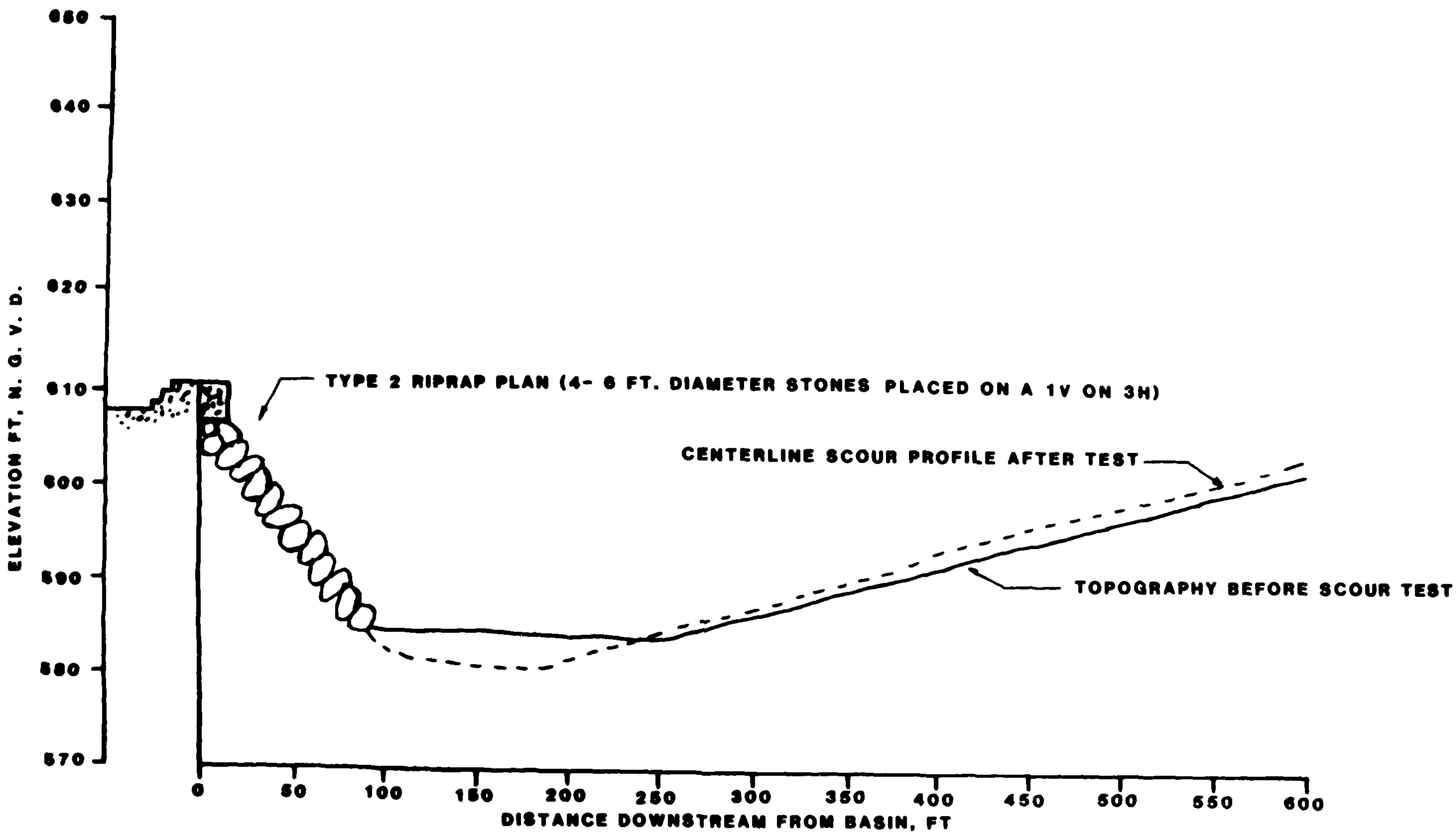
CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 626.3
GATE OPENING- 8 FT



NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

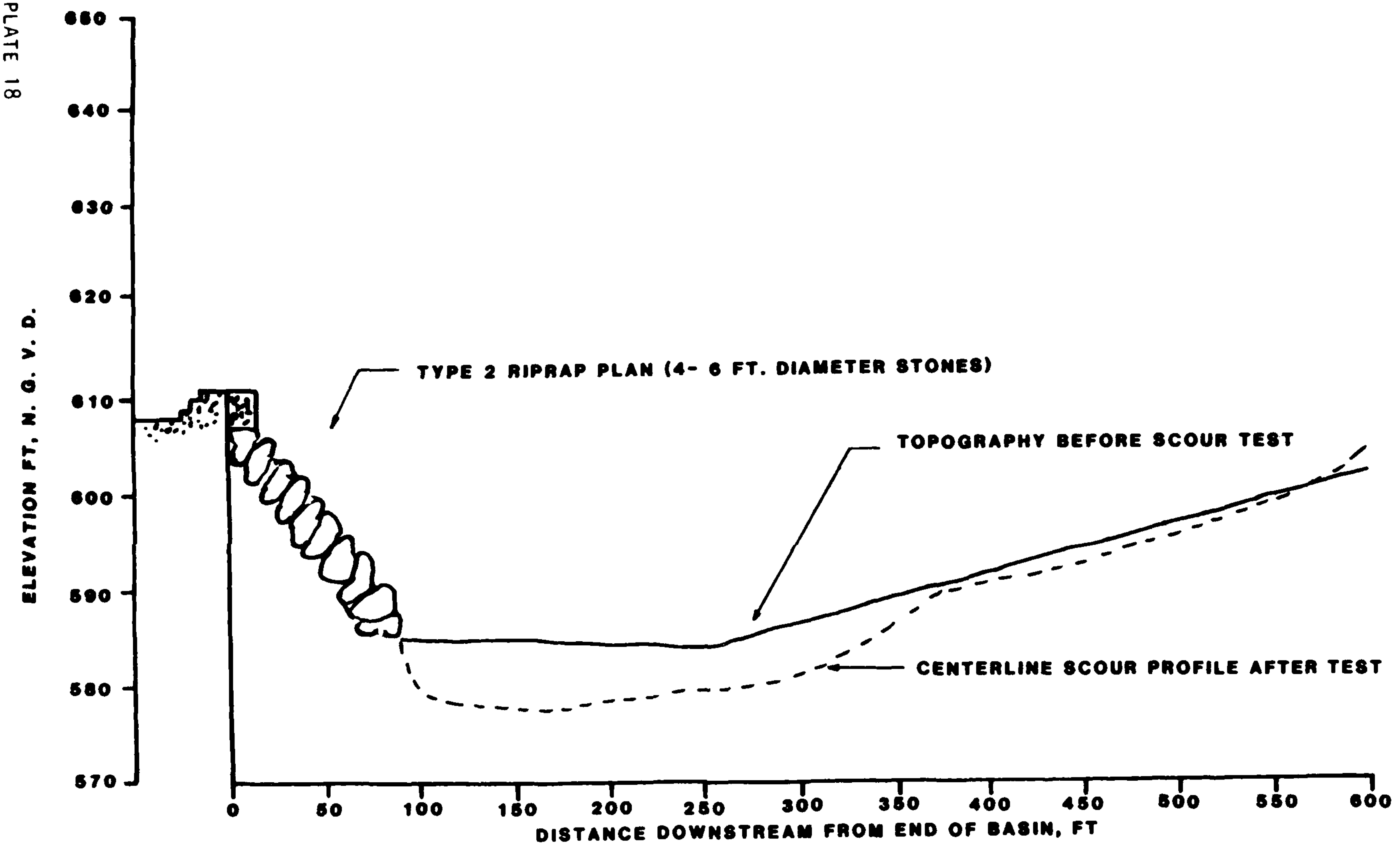
CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 635.4
GATE OPENING- 8 FT

PLATE 16



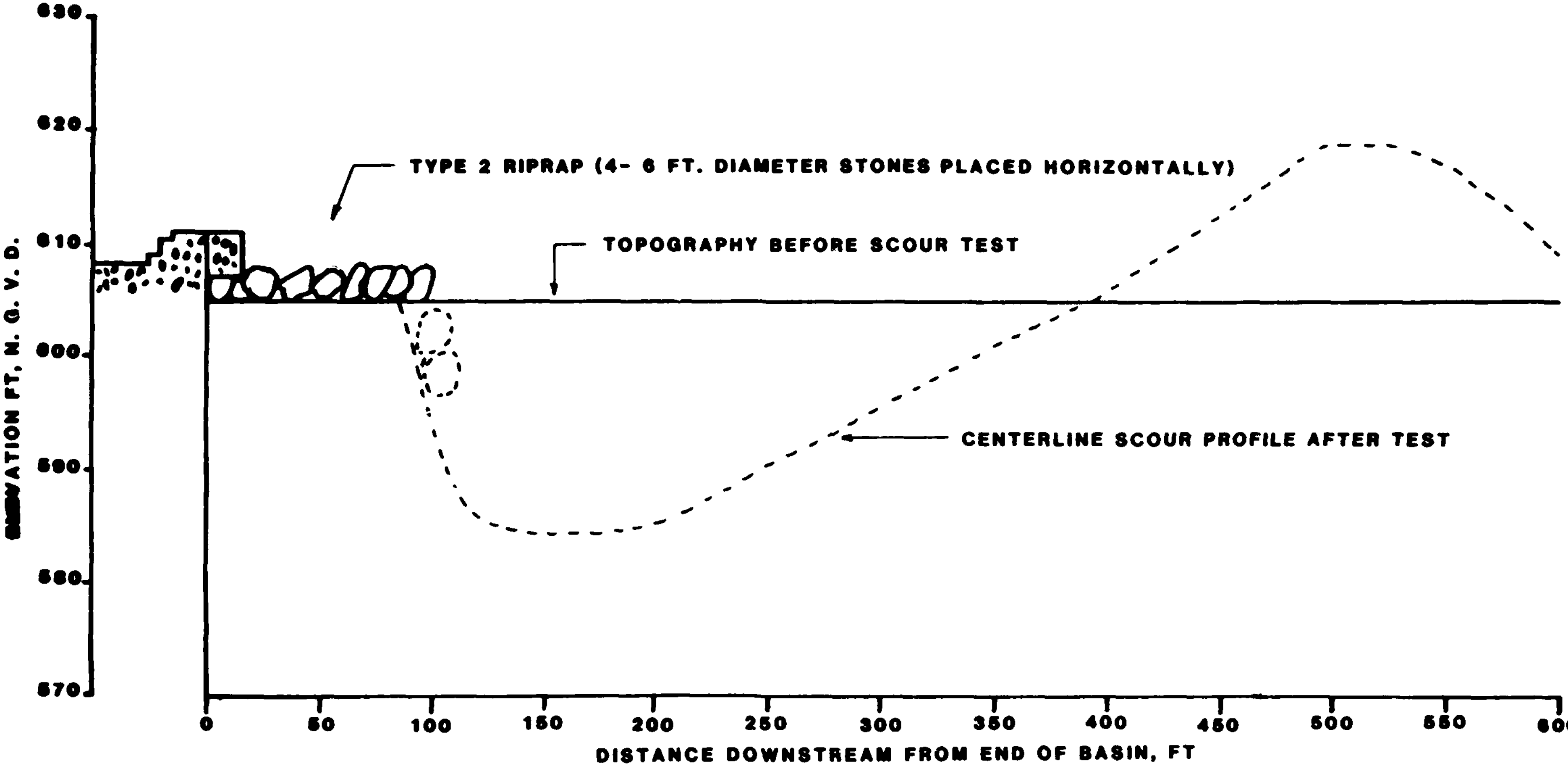
NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL-634.0
UNCONTROLLED FLOW



NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

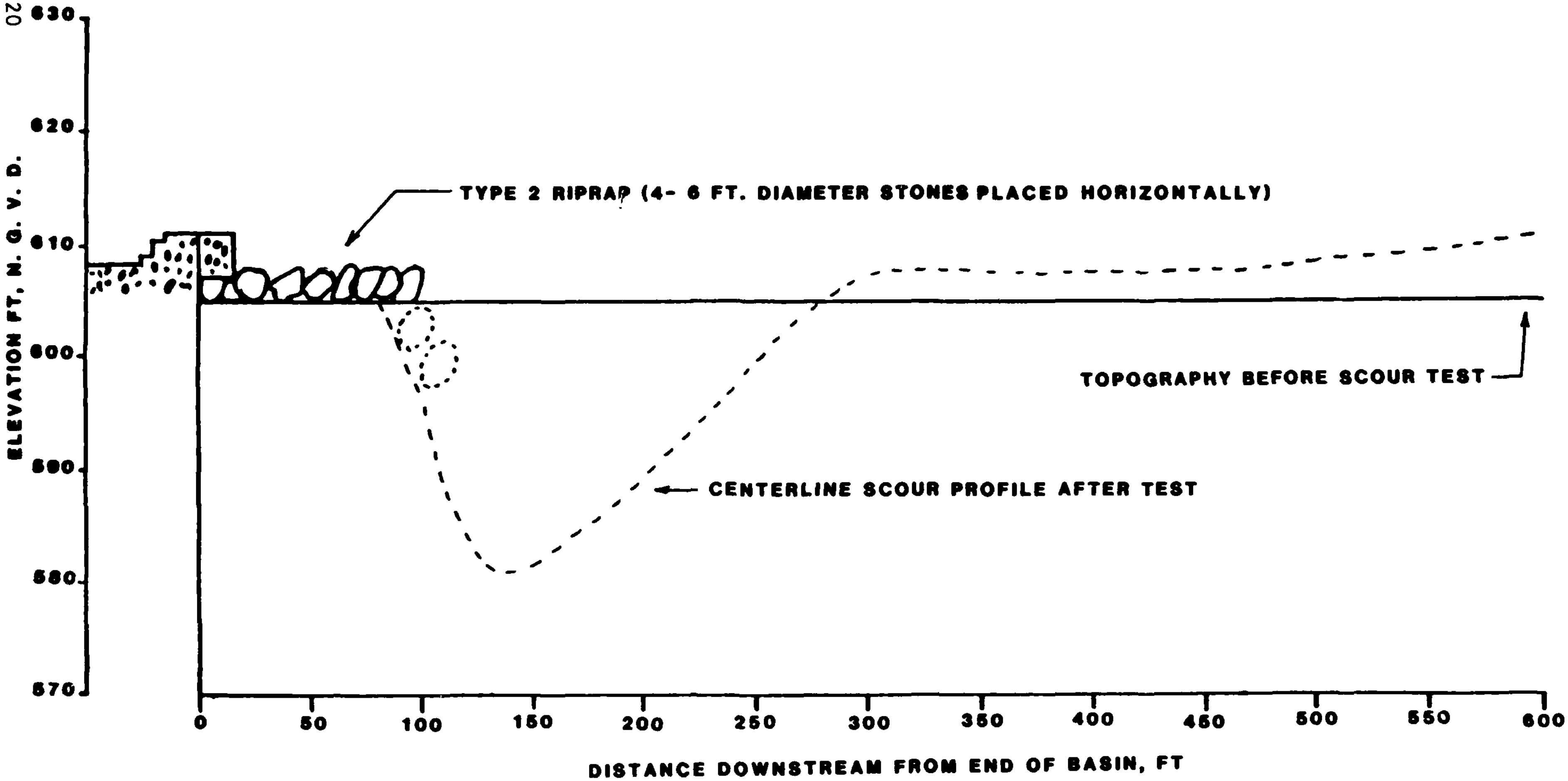
CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 636.0
GATE OPENING- 14 FT



NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

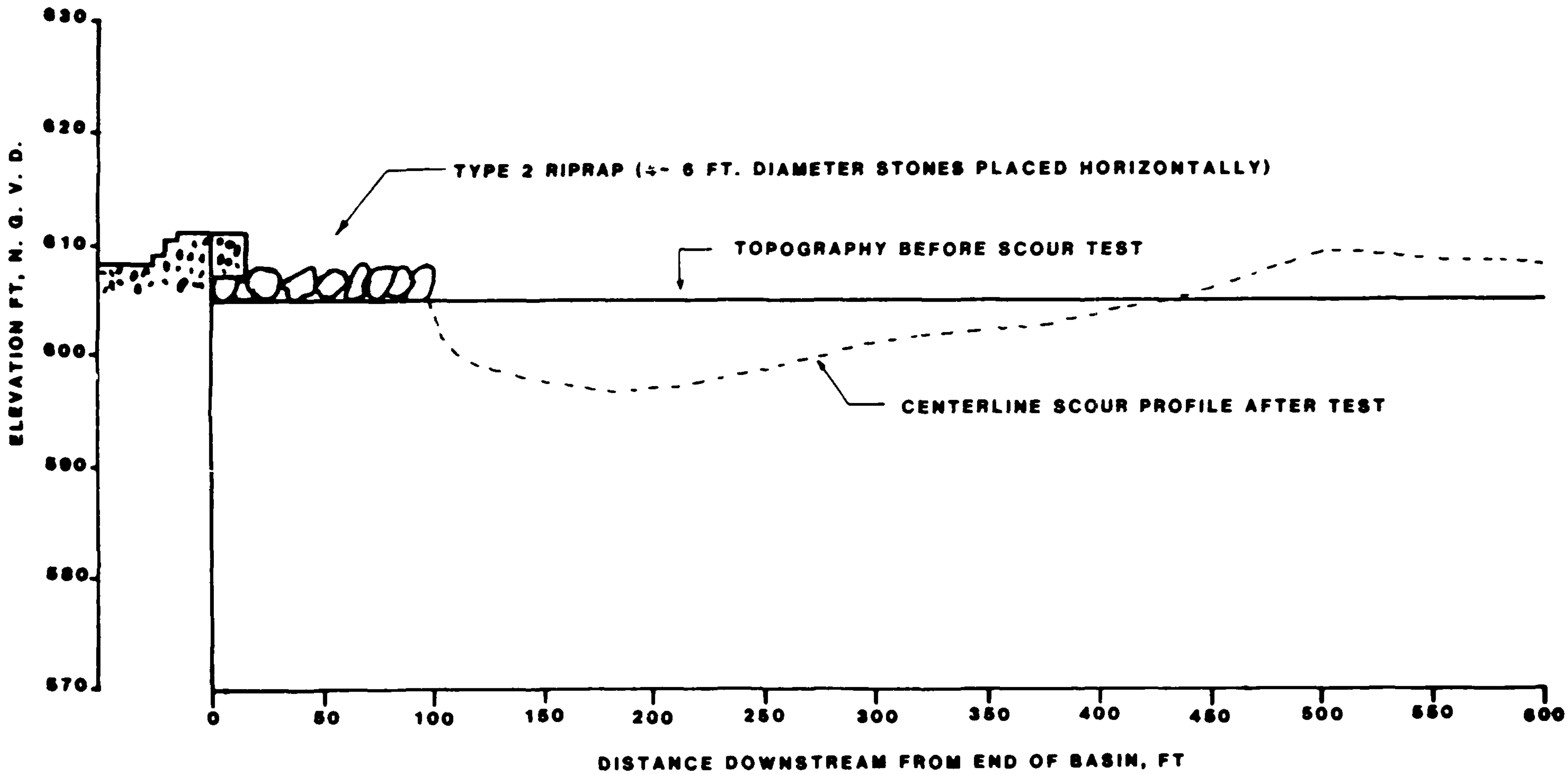
CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 637.0
UNCONTROLLED FLOW

PLATE 19



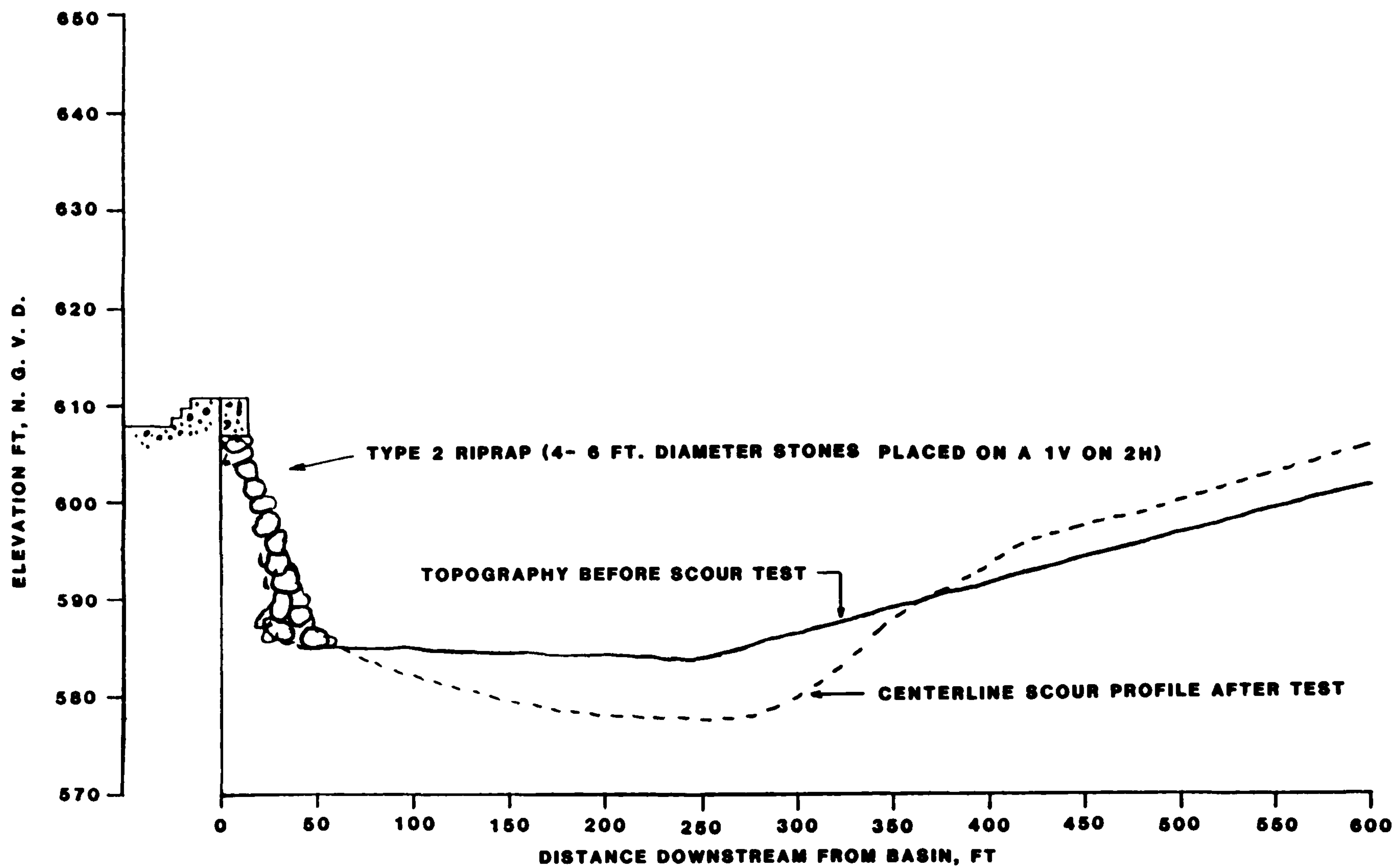
NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 636.0
GATE OPENING- 14 FT



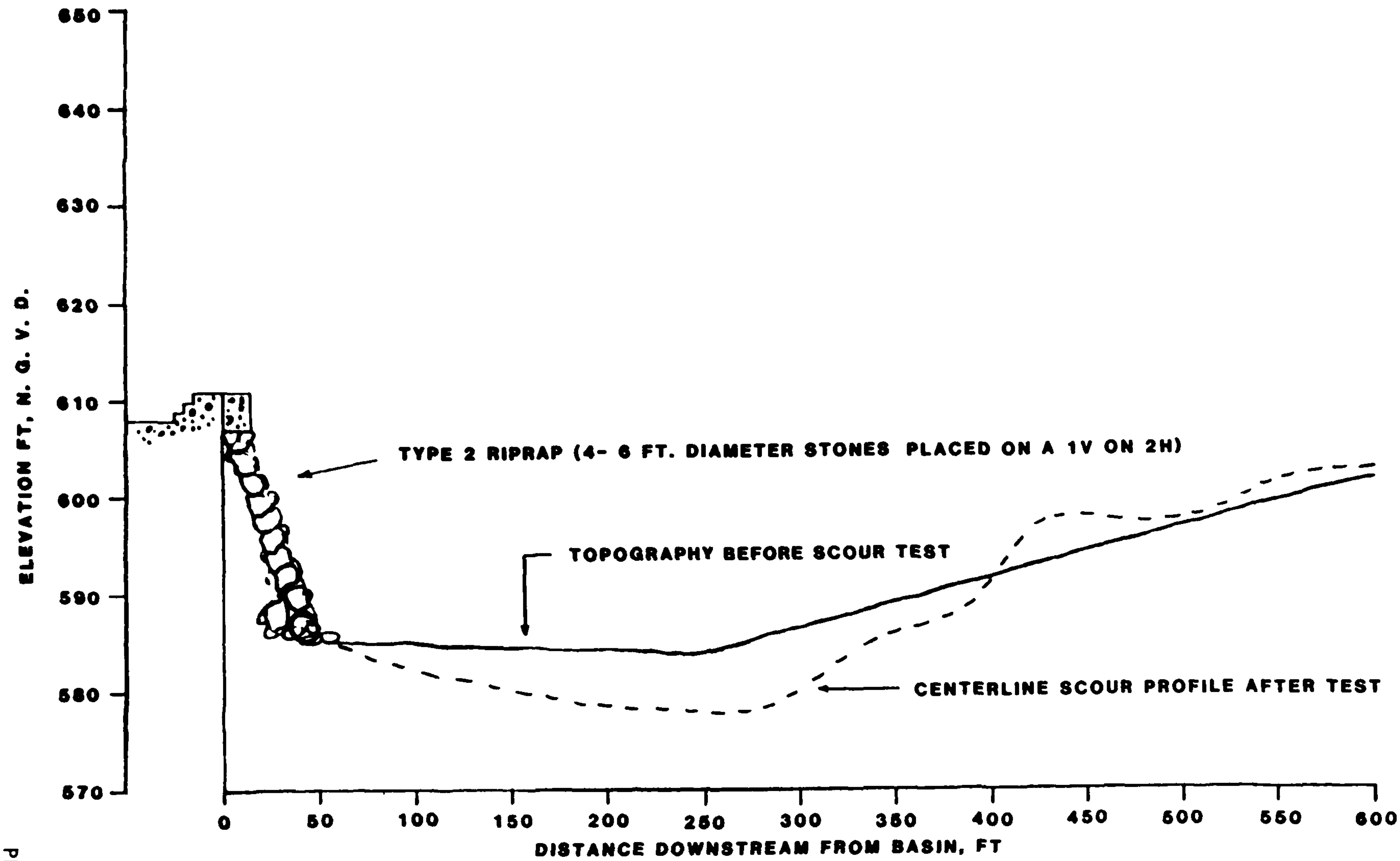
NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 623.0
GATE OPENING- 8 FT



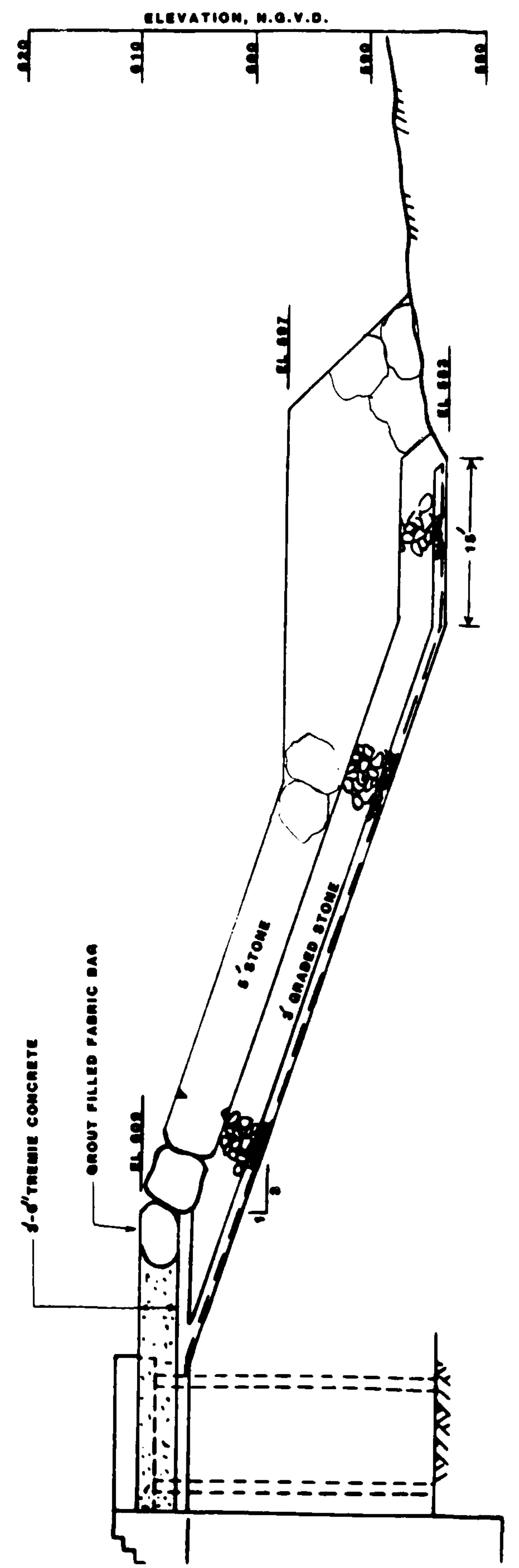
NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL- 634.0
UNCONTROLLED FLOW



NOTE: SCOUR IN EXIT CHANNEL
AFTER 5 HOURS OF OPERATION

CENTERLINE SCOUR PROFILE
UPPER POOL EL- 644.0
TAILWATER EL-634.0
GATE OPENING- 14 FT



RECOMMENDED PLAN

END

FILMED

MARCH, 1988

DTIC